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OXYGEN EQUIPMENT AND RAPID DECOMPRESSION STUDIES

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16. Abstract

This is a collection of reports of evaluations of the protective capability of various oxygen systems at high altitude and during rapid decompression. Results of these studies were presented at scientific meetings and/or published in preprints or proceedings with limited distribution.

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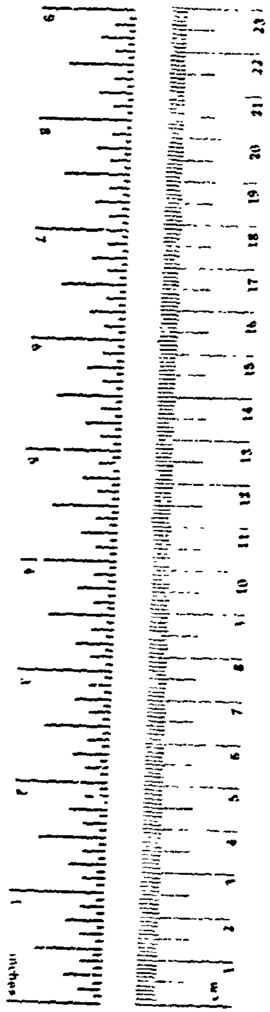
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

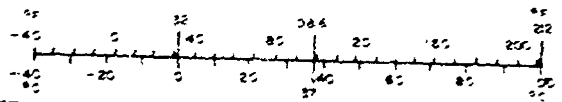
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). [illegible]



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



List of Abbreviations

BTPS - body temperature, pressure saturated

CO_2 - carbon dioxide

c/s - cycles per second

Fe - iron

FeC - iron oxide

mmHg - millimeters of mercury

N_2 - nitrogen

NaCl - sodium chloride

$NaClO_3$ - sodium chlorate

O_2 - oxygen

Pax - passenger

P_B - barometric pressure

pO_2 - oxygen partial pressure

$P_{T_{O_2}}$ - tracheal oxygen partial pressure

psi - pounds per square inch

RQ - respiratory quotient

STPD - standard temperature, pressure dry

OXYGEN EQUIPMENT AND RAPID DECOMPRESSION STUDIES

INTRODUCTION

This is a collection of reports of various studies and evaluations of the protective capability of oxygen systems and equipment used or proposed, including developmental and prototype designs for use at high altitude and/or following rapid decompression. These studies were generally designed and oriented toward (i) obtaining answers to particular questions or problems posed by Governmental approval authorities or the aviation industry with respect to the life-support capability of a given device or procedure and/or (ii) advancing the state-of-the-art in high-altitude life support and aviation safety. Certain of these reports were presented at scientific meetings and/or published in preprints or proceedings with limited distribution.

Reliable physiological evaluation of an oxygen system requires continuous determination of inspired and lung-oxygen tensions on a breath-by-breath basis. At the time these studies were conducted, analytical equipment with sufficiently rapid response to accurately measure oxygen on a breath-by-breath basis was not available; thus, development of an indirect method employing analysis of other respiratory gases and computing oxygen tensions by difference was required. The recent development of practical respiratory mass spectrometry has allowed simultaneous breath-by-breath analysis of all gases involved in respiration and has revolutionized this area of respiratory physiology and equipment evaluation. Because some of these studies were preliminary in nature and were conducted over a period of 15 yr, employing available and experimental techniques and instrumentation, information contained in these reports is subject to additional evaluation or change on review of the data, conduct of additional testing, or receipt of additional facts.

SYNOPSES OF REPORTS

Continuous Functional Testing of Passenger Oxygen Masks at Ground Level and During Rapid Decompression; Memorandum Report AAC-119-77-9(S).

This study was conducted in 1964 to improve the previously developed techniques and instrumentation for the evaluation of oxygen equipment and explore the development of methods for evaluating oxygen at ground level. The study employed a relatively large number of untrained subjects as opposed to a few selected trained subjects at altitude. A secondary, but integral, phase of the study was to evaluate a proposed passenger oxygen mask design and concurrently evaluate and compare the use of

electroencephalography and inability to maintain sequential counting as indicators of loss of useful consciousness end points. The proposed mask was unable to maintain subjects in a conscious state following rapid decompression to 40,000 ft, failed to provide the required inspired oxygen partial pressures, and was not approved until extensive redesign, modification, and reevaluation were completed.

Physiological Evaluation of a Cessna Continuous-Flow Oxygen Mask for Unpressurized General Aviation Aircraft; Memorandum Report AAC-119-77-8(S).

This study was conducted in 1966 to evaluate the physiological adequacy and protective capability of a Cessna Aircraft Company-designed modification of the disposable K-S mask developed by Koze and Stockam in 1951 for airline passenger supplemental and first aid oxygen. The proposed modification of the K-S mask was to be used on unpressurized aircraft for relatively long durations with a specific oxygen flow and oxygen line supply pressures and was to be utilized for the flight crew as well as passengers. Results of this study indicated that flows to the mask should be increased for altitudes above 25,000 ft; above 28,000 ft to 30,000 ft, a much safer alternative is the use of a nondiluting mask supplied with an adequate flow to insure 100 percent oxygen.

Performance Characteristics of Portable First Aid Chemical Oxygen Generators; Proceedings, Eleventh Annual Symposium of the Survival and Flight Equipment Association, 1973.

This study was initiated to determine the feasibility of utilizing readily available, off-the-shelf, portable first aid chemical oxygen generators marketed to the medical profession for first aid application aboard aircraft. This investigation was limited to an evaluation of initiation reliability, oxygen production, physiological adequacy, and efficiency of the oxygen-dispensing device (mask) furnished with the unit.

Physiological Evaluation of the Protective Capacity of the Prototype MBU-8/P Military Passenger Oxygen Mask; Proceedings, Eleventh Annual Symposium of the Survival and Flight Equipment Association, 1973.

The rapid development of the civil air carrier jet and its operation at flight altitudes of up to 41,000 ft have been the primary impetus for the development of modern passenger oxygen systems in the event of decompression. This report describes a study conducted at the request of the U.S. Air Force of a prototype phase-dilution passenger mask developed by the Air Force to replace the K-S open-port passenger mask, which is not recommended

for use above 25,000 ft. Evaluations were oriented toward determining compliance with Federal Aviation Regulations (FAR), National Aerospace Standard (NAS) 1179, and Federal Aviation Administration (FAA) Technical Standard Order (TSO) C64. The MBU-8/P mask demonstrated adequate physiological adequacy for limited exposures at 40,000 ft.

If workloads and therefore respiratory activity are increased above those used in this study, oxygen flow to the mask should be increased to compensate for these increases in activity.

Human Factors Report of the Investigation of the In-Flight Decompression, November 2, 1973, of National Airlines Flight 27 (N60NA): A DC-10 En Route From Houston International Airport to San Francisco With 127 Persons Aboard; Memorandum Report AAC-119-74-6(S).

This study of an in-flight decompression was conducted in response to a request from the National Transportation Safety Board for assistance from this laboratory because of our background in high-altitude and rapid-decompression research. Participation in investigation of selected accidents and incidents is also beneficial to the researcher, as it provides him with an insight into real-life aviation safety problems and areas to which priority should be placed in the design of research tasks. One passenger was ejected from the aircraft and assumed to be fatally injured. Analytical study of this accident indicated a rapid decompression of the lower galley and a slower, less severe decompression of the main passenger compartment. Following submission of this report, spectral analysis of the cockpit voice recorder verified this sequence of events.

Effectiveness of a Paper Cup as an Aid to Providing Oxygen to Laryngectomee Passengers; Memorandum Report AAC-119-74-17.

This report was completed in response to a question of the validity of an operational procedure and method of administering oxygen to a laryngectomee passenger as recommended by a major airline. The lack of a reservoir bag to store oxygen between inhalations and the inefficient characteristics of the use of a paper cup are described and compared to alternative procedures.

Physiological Considerations and Limitations in the High-Altitude Operation of Small-Volume Pressurized Aircraft; 47th Annual Scientific Meeting of the Aerospace Medical Association, 1976.

This report examines the relationship of the small volume of certain jet aircraft to the rate of decompression, the location and area of possible pressurization defects, and the resultant physiological and medical consequences. It also points out the

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physiological limitations of current oxygen equipment; requirements for pressure breathing and crew recognition and reaction time; and other factors in relation to the final pressure, the rapidity of decompression, and time-altitude profile.

Oxygen Concentrations in the Vicinity of a Passenger Receiving First Aid Oxygen; Memorandum Report AAC-119-77-4(S).

To preclude providing an ignition source, smoking aboard air carrier aircraft is prohibited at arbitrary distances or at specified seat rows from passengers who are receiving first aid oxygen. The basis for these separational distance requirements and whether they are adequate or unduly restrictive are not known. Applying modern state-of-the-art analytical instrumentation, a brief preliminary study of the oxygen content of air surrounding a subject breathing 100 percent oxygen at a standard and very high flow rate was conducted to chart localized oxygen concentrations vs. distance from the subject. This study does not concern the social acceptability or health hazard potential of smoking.

CONTINUOUS FUNCTIONAL TESTING OF PASSENGER OXYGEN MASKS AT GROUND LEVEL AND DURING RAPID DECOMPRESSION

E. B. McFadden, P. C. Tang, and J. W. Young

I. Introduction.

The development of the turbine-powered aircraft with its capability to efficiently operate at high altitudes around or above adverse weather and maintain more regular schedules has provided the principal impetus for the phenomenal growth of air transportation. However, the potential of this mode of transportation could not be fully realized until development of the pressurized cabin and its associated environmental and life-support systems. Because cabin pressurization failure imposes an immediate threat to life at the altitudes at which these aircraft operate, passenger and crew oxygen systems are provided as an emergency life-support backup.

The capability of a passenger oxygen system to provide the required level of protection at altitude is highly dependent on the performance of the mask and its capability to interface with and satisfy human breathing and oxygen requirements. Passenger oxygen masks used aboard transport category aircraft are of the phase-dilution type designed to the NAS-1179 and FAA TSO-C64 of which it is a part.

The primary purposes of this study were to: (i) extend the use of passenger mask testing techniques previously developed (1) and used at ground level (2) o the testing of a limited number of subjects exposed to a rapid decompression to the maximum certified altitude of the aircraft; (ii) evaluate the use of an electroencephalogram (EEG) to indicate impending loss of consciousness; and (iii) compare the performance of a proposed passenger mask design previously evaluated under steady-state conditions at ground level (2) to its performance during the dynamics of rapid decompression to altitude, the primary condition for which it was designed.

II. Method.

Because the percentage composition of nitrogen in the ambient air at ground level and altitude (up to 80,000 ft) is quite stable (79.03%), a reliable standard reference or tracer gas in high concentration exists in the surrounding environment of the subject. When the subject is breathing 100 percent oxygen or oxygen diluted by a known amount of air, any additional nitrogen-containing air introduced by inward mask leakage may be continuously monitored and measured by nitrogen analysis on a breath-by-breath basis. More importantly, the oxygen partial pressure of the inhaled gas may be calculated by difference and

related to human oxygen requirements regardless of the altitude and the source of the diluting gases. This indirect approach is required since instrumentation with sufficiently rapid response to measure oxygen directly on a breath-by-breath basis is not currently available.

The development and evaluation of the nitrogen analysis technique for evaluating the performance of oxygen masks is described in references 1 and 2.

Five subjects who had previously received high altitude chamber training were instrumented and rapidly decompressed from 12,000 ft to 40,000 ft in 36 to 76 s. Decompression profiles were based on the predicted decompression time of four-engine turbine-powered transport aircraft after failure of a main cabin window. At least one decompression was conducted with the subject in the resting condition. The same decompression profile was repeated with the subject in the exercising condition to stimulate breathing to the levels specified in FAR Part 25. Subjects exercised on a bicycle ergometer in lieu of the treadmill used in the former study (2). Substitution of the bicycle ergometer was required because the altitude chamber ceiling height was inadequate to accommodate the treadmill. However, the bicycle ergometer was adjusted to duplicate the exercise levels employed in the previous study (2) but at an altitude of 12,000 ft just prior to decompression. Exercise was continued and oxygen flow maintained at 30 L/min BTPS during and following the rapid decompression. In addition to the determination of nitrogen, subjects were instrumented for electroencephalographic and electrocardiographic changes. Crew-type oxygen masks and demand regulators were set to the 100-percent-oxygen position before decompression for pulmonary nitrogen washout. This process was monitored and continued until the washout curve was asymptotic and the remaining nitrogen was negligible. Just prior to decompression the subjects held their breath, removed the crew masks, and donned the passenger masks with oxygen flowing at a rate equivalent to 30 L/min BTPS at 40,000 ft. The type of mask used was the same proposed passenger oxygen mask evaluated at ground level in the previous study (2). A subject's inability to maintain sequential counting and/or initiation of convulsive movements was established as the end point for loss of useful consciousness. Electroencephalographic changes were monitored and recorded for comparison of their onset, duration, and frequency as related to the development of hypoxia and loss of useful consciousness. Depending on the onset and severity of loss of useful consciousness, descent was initiated, and either the passenger mask was removed by the safety observer and replaced with a crew mask delivering oxygen under pressure or the passenger mask was flooded with oxygen. Those subjects who did not exhibit obvious symptoms of impending loss of consciousness were maintained at altitude for at least 5 min before descent was initiated.

Measurement and establishment of minute and tidal volumes were made while subjects were wearing the crew masks just prior to donning the passenger masks and decompression. When a constant-flow passenger mask is worn, current techniques and instrumentation do not allow measurement of respiratory volumes without compromising mask performance. The dynamics of rapid expansion of gases in the lungs during decompression increases the difficulty of accurately determining respiratory volumes.

In addition, any type of gas analysis equipment that requires a relatively large sample flow or volume compromises mask performance. Respiratory nitrogen was monitored and recorded by using two Custom Engineering Model 300AR nitralyzers. These instruments have a rapid response time and required only 3 cc/min of sample at the pressure setting used. Continuous samples were drawn from the mask through a needle valve and microcatheter tubing of 0.03-in inner diameter. This small, extremely lightweight microcatheter tubing did not add significant weight to the mask or necessitate its modification (factors affecting the characteristics and performance of the mask) as may be the case with other types of gas analysis equipment. One of the nitralyzers was used to record minimum and maximum nitrogen on a breath-by-breath basis, whereas a small inline sample mixing and damping reservoir was used to attempt to integrate and determine the average or mean nitrogen concentration by the other nitralyzer (Table 1). Nitralyzers were calibrated and matched before each experiment.

Tracheal oxygen partial pressures were estimated as follows:

$$P_{T_{O_2}} = 100 - F_{N_2} \ (B-47)$$

where 100 = sum of nitrogen and oxygen in the inspired gas

F_{N_2} = fraction of nitrogen in the inspired gas

B = barometric pressure at ambient altitude in mmHg

47 = vapor pressure of water in mmHg at body temperature (37°C)

$P_{T_{O_2}}$ = tracheal oxygen partial pressure

TABLE 1. Nitrogen Concentration and Calculated Tracheal Oxygen Partial Pressure of Subjects Rapidly Decompressed From 12,000 to 40,000 Feet Wearing the Passenger Test Mask

Subject	Condition	Percent N_2 at 30 L/min O_2 Mean	Percent N_2 Peak Min.	Percent N_2 Peak Max.	Percent Leakage at 30 L/min O_2 Mean	Percent Leakage Peak Min.	Percent Leakage Peak Max.	Tracheal O_2 Partial Pressure $P_{T_{O_2}}$ (mmHg)	$P_{T_{O_2}} \pm$ 83.8 mmHg FAR 25.1443	Tidal Volume (BTPS) Before Decompression (cc)
1	Resting	17	11	44	22	14	57	78	- 5	
	Exercising	45	12	67	58	15	86	52	-32	1,100
2	Resting	9	8	12	12	10	15	86	2	
	Resting	40	18	55	52	23	71	56	-27	
	Exercising	45	28	68	58	36	88	52	-32	1,200
3	Resting	31	6	65	40	8	84	65	-18	
	Resting[1]	24	12	67	31	15	86	101		
	Exercising	42	19	68	54	24	88	55	-29	1,200
4	Resting	17	11	44	22	14	57	78	- 5	
	Exercising	43	23	65	55	30	84	54	-30	1,000
5	Resting	37	14	52	48	18	67	59	-24	2,500[2]
	Exercising	32	15	47	41	19	61	64	-19	1,000

[1]decompression from 12,000 to 35,000 ft.
[2]subject hyperventilating.

TABLE 2. Comparison of One or More Decompressions With the Subject at Rest to a Similar Decompression During Light Exercise (Decompression Profile: 12,000 to 40,000 ft)[1]

Subject	Condition	Decompression Time (s)	Time at Altitude (s)[2]	$P_{T_{O_2}}$ (mmHg)	EEG Results (time in s at altitude) (slow waves in c/s)	Descent Initiated (s at altitude)
1	Resting	40.5	---	78	No slow waves observed	444
	Exercising	41.0	69	52	6 c/s, appeared at 57 s. 3-4 c/s, appeared at 77 s. 3-4 c/s, ended at 107 s.	94
2	Resting	76.0	---	86	No slow waves observed.	418
			183	56	4-7 c/s, appeared at 167 s. 4-7 c/s, ended at 214 s.	219
	Exercising	39.0	51	52	3 c/s, appeared at 52 s. 3 c/s, ended at 76 s.	60
3	Resting[1]	36.0	---	101	6-7 c/s, appeared at 347 s. 3-4 c/s, appeared at 386 s. 3-4 c/s, ended at 409 s. 6-7 c/s, ended at 474 s. All above occurred intermittently.	484
	Resting	41.0	67	65	7 c/s, appeared at 15 s. 3 c/s, appeared at 47 s. 3 c/s, ended at 103 s. 7 c/s, ended at 129 s.	94
	Exercising	46.0	41	55	6-7 c/s, appeared at 14 s. 3-5 c/s, appeared at 25 s. All slow waves ended at 72 s.	49

(Continued on following page)

TABLE 2 (continued)

Subject	Condition	Decompression Time (s)	Time at Altitude (s)[2]	$P_{T_{O_2}}$ (mmHg)	EEG Results (time in s at altitude) (slow waves in c/s)	Descent Initiated (s at altitude)
4	Resting	46.0	---	78	6-7 c/s, appeared at 78 s. High voltage slow waves 6-7 c/s appeared at 128 s. High voltage 6-7 c/s ended at 234 s. 7 c/s, ended at 327 s. 8 c/s, ended at 428 s.	436
	Exercising	47.0	36	54	6 c/s, appeared at 16 s. 2-3 c/s, appeared at 34 s. All slow waves ended at 56 s.	45
5	Resting	37.0	250	59	6 c/s, appeared at 170 s. 3 c/s, appeared at 235 s. 3 c/s, ended at 245 s. 7 c/s, ended at 275 s. All above occurred intermittently	270
	Exercising	40.0	98	64	6 c/s, appeared at 101 s. 6 c/s, ended at 152 s.	138

[1]Subject No. 3, Resting, was decompressed from 12,000 to 35,000 ft.

[2]Dashed line indicates that the subject's physiological condition was satisfactory and descent was initiated at the indicated time.

Subjects wearing the mask were exposed to a rapid decompression in the altitude chamber to support this conclusion. During light exercise following decompression from 12,000 to 40,000 ft, the subjects wearing this mask maintained useful consciousness for periods of only 36 to 98 s (Table 2). The one subject (a high-altitude researcher) who was capable of maintaining useful consciousness for a period of 98 s has, by the process of acclimatization and hyperventilation, previously demonstrated an ability to maintain consciousness without oxygen for record periods of 30 min at 30,000 ft. He was observed hyperventilating, possibly from habit, with a tidal volume in excess of 2,500 cc during the resting decompression. Hyperventilation and large tidal volumes tended to increase both leakage and oxygen dilution when this subject wore a phase-dilution passenger mask, thus accelerating the onset of hypoxia with the result that he was forced to descend before the 5-min dwell at altitude was completed. In his succeeding decompression while exercising he appeared to be overcompensating by breathing slowly and shallowly, thereby maintaining useful consciousness for a period of 98 s, considerably longer than any of the other subjects during exercise. This subject's data should not be considered representative. These data point out, however, both the deleterious and advantageous effects one may exert on the performance of this type of oxygen mask by the introduction of voluntary hyperventilation and hypoventilation.

Mean heart rates increased considerably during decompression and dwell at altitude, returning to the preflight level on descent to ground level (Table 3). This increase indicates that a certain amount of apprehension and stress was associated with the decompression which, in turn, would produce increases in minute and tidal volumes over the levels established just prior to decompression. Direct measurement of minute and tidal volumes was not possible, however, when the passenger masks were worn during decompression.

Increases in minute and tidal volumes as a result of apprehension and stress, when superimposed on those levels established during exercise prior to decompression, could well have increased ventilation above experimental design levels. Increased ventilation and the resultant leakage could account in part for the tracheal oxygen partial pressures being considerably lower than predicted from the previous study at ground level (2). Of prime interest, however, is that in only one instance, even when the subject was quietly resting, did the tracheal pO_2 following decompression to 40,000 ft meet the minimum requirement of Part 25.1443 of the FARs (Table 1). The approximate point at which exercising subjects lost useful consciousness, as determined by their inability to continue sequential counting, is compared to the onset, frequency, and duration of electroencephalographic slow waves as shown in Table 2 and Figure 1.

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TABLE 3. Decompression Profiles, Heart Rates, and Exposure Times of Subjects Wearing the Passenger Test Mask (Decompression Profile: 12,000 to 40,000 ft)[1]

Subject	Condition	Heart Rates Preflight	Heart Rates Decompression	Heart Rates Postflight	Decompression Time (s)	Inability to Maintain Sequential Count (time in s)[2]	$P_{T_{O_2}}$ (mmHg)	Descent Initiated (s at altitude)
1	Resting	60	81	57	40.5	---	78	444
	Exercising	72	117	78	41.0	69	52	94
2	Resting	72	72	60	76.0	---	86	418
	Resting[1]	112	108	84	41.0	183	56	219
	Exercising	72	121	66	39.0	51	52	60
3	Resting	60	129	60	41.0	67	65	94
	Resting	72	93	69	36.0	---	101	484
	Exercising	78	126	60	46.0	41	55	49
4	Resting	72	126	81	46.0	---	78	436
	Exercising	60	96	66	47.0	36	54	45
5	Resting	54	66	54	37.0	250	59	270
	Exercising	57	90	57	40.0	98	64	138

[1]Subject No. 3, Resting Condition noted, was decompressed from 12,000 to 35,000 ft.
[2]Dashed line indicates that the subject's physiological condition was satisfactory and descent was initiated at the indicated time.

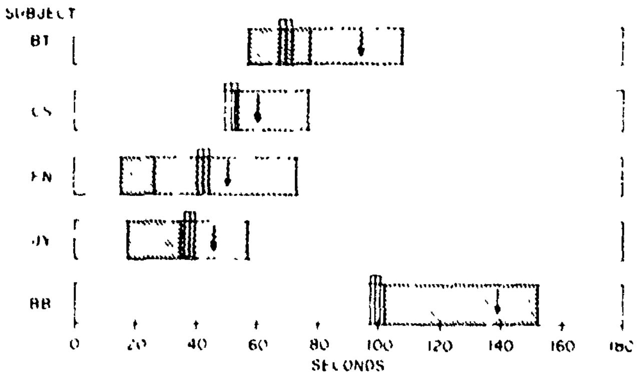

FIGURE 1. Comparison of electroencephalographic slow waves to loss of useful consciousness following rapid decompression from 12,000 to 40,000 ft. Passenger oxygen mask flow 30 liters per minute. Light exercise on bicycle ergometer.

Loss of useful consciousness (inability to maintain sequential counting)

6-7 cycle slow waves

Emergency descent

3-4 cycle slow waves

IV. Discussion.

To conserve the oxygen supply and extend its duration, passenger oxygen systems and masks used on transport category aircraft are designed to provide reduced oxygen flows and allow specific quantities of ambient air to enter the mask through the dilution valve at lower altitudes to meet human breathing (ventilation) requirements. However, the minimum oxygen partial pressures as specified in the FARs must be maintained. As the altitude is increased, oxygen flow must be increased and dilution decreased or eliminated as the maximum cabin altitude is approached. Uncontrolled dilution by inward leakage of nitrogen-rich ambient air reduces the efficiency of the mask and may jeopardize its protective capability. This factor is variable, depending on the design and fit of the mask and the facial configuration and structure of the wearer.

In the absence of leakage associated with fit, the performance of a phase-dilution mask is largely dependent on oxygen flow, inhalation and dilution valve sequencing, reservoir bag volume, and respiratory activity of the wearer. By literally flooding the mask with oxygen, inward leakage may be minimized or even converted to outward leakage; however, to flood the mask could require an

eightfold or greater increase in the number of oxygen cylinders installed on the aircraft, imposing severe and unacceptable space and weight penalties.

Use of the minimum or maximum concentration of nitrogen for the calculation of tracheal oxygen partial pressures is not justified because: (i) the minimum concentration of nitrogen may be attained as a result of a constant flow of oxygen washing out the mask dead space; or (ii) the maximum concentration of nitrogen during peak dilution in the mask occurs through the introduction of ambient air by the dilution valve. The mean nitrogen concentration appears to provide a more realistic value and was utilized in this study for computation of the tracheal oxygen partial pressure. A more precise and accurate determination of the tracheal oxygen partial pressure while wearing a mask should be based on breath-by-breath analysis of all end expiratory gases as a basis for determination of the partial pressures of these gases in the air sacs (alveoli) of the lungs. New developments in instrumentation with improved sensitivity and response, including the use of polarographic gas analysis and mass spectrometry, may allow direct determinations of all alveolar gases practical on a routine basis.

It is not surprising that the tracheal oxygen partial pressures were considerably lower following rapid decompression than those predicted in previous testing (2) at ground level. During the dynamics of decompression, a number of effects prevail that are absent under steady-state ground-level conditions. These include rapid expansion of gases in the lungs and accelerated diffusion of carbon dioxide into the alveoli of the lungs as a result of reduced pressure. The accelerated diffusion of carbon dioxide into the alveoli displaces oxygen, thereby increasing the level of hypoxia. Once initiated, hypoxia-induced hyperventilation tends to increase the dilution of oxygen delivered by the mask thus establishing a vicious cycle which is directed toward further increasing the level of hypoxia.

As alveolar oxygen partial pressure is in near equilibrium with the blood, determination of the partial pressures of alveolar gases provides a more precise indication of the physiological condition of the mask wearer. However, a mask (as an item of equipment) is, in itself, only capable of delivering a breathing mixture with an increased oxygen partial pressure. This philosophy is reflected in the passenger oxygen requirements of the FARs.

Carbon dioxide in the blood exerts a significant effect on the control of respiration and, in conjunction with other controlling mechanisms, normally regulates and maintains a carbon dioxide partial pressure of 40 mmHg in the alveoli of the lung. By applying a derivation of the alveolar equation, the partial pressure of carbon dioxide may be subtracted from the tracheal

oxygen partial pressures of Table 1 and values may be estimated for alveolar oxygen partial pressures as follows:

$$P_{A_{O_2}} = P_{T_{O_2}} - P_{A_{CO_2}} \text{ or, in simple form, } P_{A_{O_2}} = P_{T_{O_2}} - 40$$

where $P_{T_{O_2}}$ = tracheal oxygen partial pressure

P_{CO_2} = alveolar carbon dioxide partial pressure

$P_{A_{O_2}}$ = alveolar oxygen partial pressure

The average alveolar oxygen partial pressure of the resting subjects following decompression to 40,000 ft calculated by the above method was approximately 30 mmHg. It is generally accepted that alveolar oxygen partial pressures in the range of 20 mmHg to 35 mmHg (zone of performance degradation) may be expected to produce mild to severe performance degradation. Below 20 mmHg (zone of unconsciousness), pressures in this range will produce imminent loss of consciousness. The alveolar oxygen partial pressure of the subjects while exercising averaged 15 mmHg. The reactions of the subjects, including useful consciousness determinations and electroencephalographic findings as shown in Tables 2 and 3 and Figure 1, support the alveolar oxygen partial pressures calculated above.

Previous ground-level evaluations of the proposed passenger mask (2) indicated that it did not provide the minimum tracheal oxygen partial pressures required by Part 25 of the FARs when evaluation was extended to the maximum altitude for which approval was sought. Decompression of subjects to the maximum altitude produced even lower tracheal oxygen partial pressures, resultant hypoxia, and loss of useful consciousness (as determined by the subjects' inability to maintain sequential counting) in several subjects while resting and in all the subjects while engaged in light exercise. The passenger oxygen mask evaluated in this study did not provide the minimum tracheal oxygen partial pressures required by Part 25.1443 of the FARs and should not be approved for use on transport category aircraft.

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PHYSIOLOGICAL EVALUATION OF A CESSNA CONTINUOUS-FLOW OXYGEN MASK FOR UNPRESSURIZED GENERAL AVIATION AIRCRAFT

E. B. McFadden, H. F. Harrison, and J. M. Simpson

I. Introduction.

This report describes altitude chamber experiments conducted with human subjects using a Cessna-designed disposable oxygen mask. Basically, the mask is almost identical in design to the disposable K-S mask developed by Koze and Stockam in 1951 (under the guidance of Dr. A. D. Tuttle of United Air Lines) for passenger supplementary and first aid oxygen (1). Using new types of material, the designers have attempted to produce a mask that will provide a better seal to the face and increase comfort, durability, efficiency, and wearer acceptance for relatively long durations at altitude in unpressurized aircraft.

The mask is of the rebreather-diluter type with a regulated constant flow of oxygen provided to the rebreather portion of the mask. The mask consists of two flexible plastic film compartments. The smaller or facepiece compartment is sealed within the larger or rebreather bag. Two holes connect the facepiece to the rebreather bag to allow gaseous exchange with the oxygen supply and rebreather bag. Two additional dilution ports are provided in the facepiece to allow access to ambient air. The mask is retained to the face by means of an elastic band. The soft metal wire encased in pliable plastic, which forms the periphery of the mask facepiece, is formed to the contours of the face for a proper fit. Prototype masks were fabricated in three basic sizes: small, medium, and large.

Determination of efficiency of an oxygen system must be based on the system's capability to produce an adequate inspired oxygen partial pressure resulting in a sufficient alveolar oxygen partial pressure in the lungs to insure a blood oxygen saturation of an acceptable level.

Physiological responses to minor changes in oxygen partial pressure vary widely depending on factors such as age, general physical condition, and/or the presence or absence of cardiac, circulatory, or respiratory pathology.

One basic disadvantage of all continuous-flow oxygen systems is an inability to adjust automatically to the respiratory changes associated with changes in emotional and physical activity of the wearer. A healthy young male breathing air at rest normally exhibits an approximate tidal volume (volume/breath) of 550 ml. and a minute volume (volume/min) of 7,700 ml. or 7.7 L. Emotional and/or physical activity may cause values to increase many fold.

II. Methods.

The study was divided into three phases. The first phase was conducted with 10 volunteer subjects, 6 males and 4 females, ranging from 15 to 44 yr of age. Two of the male subjects and all the female subjects were considered naive subjects as they had no prior experience in altitude chamber flight. The remaining four males had previously been exposed to one or two chamber flights but would not be considered to have had extensive experience.

The altitude chamber flight profile for each of the 10 subjects is shown in Figure 1. Electrodes were affixed to the subject to obtain ECG, heart rate (cardiotachometer), and respiration (impedance pneumograph). An oximeter earpiece was affixed to the pina of the ear of the subject to obtain a measure of blood oxygen saturation. The information was fed to appropriate amplifiers and signal conditioners, monitored and recorded continuously on a physiograph recorder (Figures 2 and 3) throughout the altitude chamber flight.

The operators of this equipment could observe the subject at all times by use of closed-circuit television. In addition, a safety observer accompanied each subject in the chamber.

Two Custom Engineering and Development Company nitralyzers, Model 300 AR, were used to continuously measure the mask nitrogen. These instruments exhibit an initial response of 0.024 second, a 90-percent response being obtained in 0.044 second. At the pressure setting used (0.6 mmHg), the sampling rate was 3 cm^3/min.

Continuous samples were drawn through needle valves and microcatheter tubing (PE 60) of 0.030-in internal diameter connected into the facepiece and rebreathing compartments of the mask. The small, extremely lightweight microcatheter tubing connected to the mask did not require addition of significant weight or modification of the mask, factors that might compromise the fit and operational characteristics of the mask.

After instrumentation, subjects were seated in the chamber and ground-level baselines recorded (Table 1). An ascent was made to 10,000 ft and a descent was made to 5,000 ft to determine the subject's ability to clear ear pressure before ascending to higher altitudes. The chamber ascended to 14,000 ft and air-breathing baselines were recorded during 3 min of resting and 3 min of light exercise (Table 2). The mask, equipped with a Zep-Aro orifice (F 365-1080-2) operating at a supply pressure of 70 psi and providing 2.7 L/min STPD, was donned. This pressure and flow were maintained throughout the first phase of the evaluation. Observations of blood oxygen resaturation were made on

several subjects within 1 min after they donned the mask at 14,000 ft and subsequently after 1 and 3 min of exercise (Table 3). Determination of mask nitrogen was naturally not available until after mask donning was accomplished.

Following mask donning an ascent was made to 20,000, 25,000, and 30,000 ft with a dwell time of 6 min at each altitude. During the first 3 min at each altitude the subject engaged in light exercise, using a bicycle ergometer at a speed of 40 r/min and load of 50 W (approximately equivalent to walking at 3.0-3.4 mi/h) (Tables 4-12). During the last 3 min the subject read articles from aviation or similar magazines through the mask into a recorder microphone.

Postflight ground-level determinations of resting blood saturation, heart, and respiratory rates were recorded on six subjects (Table 13) in conjunction with carbon dioxide measurements at ground level while wearing the mask (Table 14). An LB-1 infrared gas analyzer was utilized to determine the carbon dioxide in the mask facepiece and rebreather bag. The relatively high flow requirements (500 mL/min) of this analyzer dictated that the sample be circulated through the analyzer and returned to the mask compartment from which it was removed. This process appeared to significantly modify the breath-by-breath nitralyzer measurements; therefore, carbon dioxide measurements were conducted only at ground level. Since flow at ground level in terms of BTPS is at its lowest and mask ventilation is minimal, this condition should represent the worst probable condition for carbon dioxide accumulation.

Tape recordings of the subjects reading at altitude were subjectively evaluated for intelligibility in terms of volume and clarity by a former radioman (now a sound technician) who was unfamiliar with the content of the recordings (Table 15).

Two of the ten subjects included in the first phase of the evaluation, duplicated the first flight profile wearing a different type mask. The first subject (BH) wore the Zep-Aro constant-flow mask (Cessna Part No. C 166009-0401) (Tables 16-17). The other subject (DZ) wore the Ohio Chemical Company K-S mask (Tables 18-19). The same orifices and oxygen supply pressure were maintained as in the previous 10 subject flights.

In view of the probable use of the mask at altitude for relatively long periods of time, it becomes apparent that additional evaluations should be conducted for extended duration to produce a more reliable steady-state condition of the unacclimatized subject. In this second phase of the evaluations the subject remained at altitude for 1 h with alternate periods of activity and rest extended to about 6 min of light exercise and

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about 10 min of rest. Two 1-h evaluations using the same subject are shown in Tables 20 and 21. The first was conducted at 25,000 ft at an oxygen supply pressure of 70 psi. For the second flight the pressure was reduced to 60 psi.

An extended 1-h flight at 30,000 ft of subject JV (Tables 22-23) was aborted after 32 min because of the steady deterioration of the subject's blood oxygen saturation during light exercise and, as a precautionary measure, because of the safety observer's developing a light case of bends.

In the evaluation of oxygen mask efficiency, one of the most important factors is the partial pressure of gases in the inspired air. A rebreathing mask defies direct measurement of these parameters because of the rapidly varying nonhomogeneous gas mixtures introduced from instant to instant in the facepiece of the mask.

To estimate the composition of inspired gases, we pursued a different indirect approach. This technique is based on the assumption that the end expiratory gases from the lungs have mixed and represent a homogeneous mixture.

As an inert gas, nitrogen does not participate in metabolic exchange. If the absorption of oxygen and the production of carbon dioxide were exactly the same, then the amount of nitrogen inspired would equal the amount expired; i.e., nitrogen molecules inspired = nitrogen molecules expired. The respiratory metabolic RQ would be equal; i.e., RQ = 1. The metabolic RQ (i.e., RQ = $\frac{CO_2 \text{ produced}}{O_2 \text{ consumed}}$) is not normally exactly equal. Under these conditions there may be a relative difference in the percentage of inert nitrogen inspired and expired. The metabolic RQ depends on the predominance of carbohydrates (1.0), protein (0.82) or fat (0.71) in the diet. The normal value of a mixed diet approximates 0.83. The respiratory RQ may vary temporarily from the metabolic RQ because of unsteady states, such as hyperventilation. The increased lung ventilation produces a blowoff of carbon dioxide from the blood and an apparent but misleading increase in carbon dioxide production with a resultant RQ greater than 1.0. Conversely, hypoventilation and retention of carbon dioxide indicate an apparent but misleading decrease in carbon dioxide production that results in an RQ of less than 0.7.

One must keep in mind that the unequal exchange of oxygen and carbon dioxide involves only that portion of the gases consumed and produced. For example, if during the 1-min period at rest 0.3 L of oxygen was consumed and 0.25 L of carbon dioxide was produced (RQ = 0.83), the resultant difference of 0.05 L on the 7 or 8 L passing through the lungs during the same period of time is relatively small. This produces an error of only a few

percentage points, well within the accuracy of determinations of end expiratory nitrogen.

All nitrogen diluting the inspired gas originates from ambient air with the exception of nitrogen derived from the tissues, which after 6 to 8 min under a steady-state condition has been shown to constitute less than 1 percent of the lung volume (2).

Using calculations suggested by Luft (3) in 1951, one can determine the admixture of air; i.e.:

$$\frac{\text{Admixture of air}}{100} = \frac{\text{Inspired nitrogen fraction}}{\text{Nitrogen fraction of air}}$$

By substituting end expiratory nitrogen for inspired nitrogen:

$$\text{Admixture of air} = \frac{\text{End expiratory nitrogen}}{\text{Nitrogen fraction of air}}$$

Using these formulas one may derive the percentage of dilution, supply oxygen, oxygen from the ambient air, and total oxygen according to the following calculations:

$$\text{Percent Dilution} = \frac{\text{End Expired } N_2 \times 100}{N_2 \text{ of Air } (79.03)}$$

Oxygen from Supply = 100 - Percent Dilution

Oxygen from Ambient = Percent Dilution x Ambient Oxygen (20,94)

Total Oxygen = Oxygen from Supply + Oxygen from Ambient

Calculated inspired oxygen partial pressure =
$(P_B - 47) \times$ Percent Total Oxygen

Where: P_B = Total pressure in mmHg at ambient altitude

47 = Pressure in mmHg of saturated water vapor at body temperature

The average percentages of supply oxygen during reading and exercising of the 10 subjects in the first phase are presented in Figure 6 for comparison with Luft's determination on the K-S mask in 1951 (Figure 7).

Data showing the concentration of inspired oxygen using the Cessna mask are superimposed over Luft's plot of the result obtained on the K-S mask in 1951 (Figure 8).

III. Results.

The ground-level blood oxygen saturation, heart, and respiratory rates of the 10 subjects in Table 1 appear normal with the exception of some elevation of heart and respiratory rates of several subjects. This response appeared to be a result of some degree of apprehension. There was considerable variation in blood oxygen saturation baselines breathing air at 14,000 ft. The lowest average value of 86.6 percent was obtained in the sixth minute at 14,000 ft following 3 min of light exercise. The lowest single individual saturation was that of subject BH, who exhibited a 78-percent saturation after 3 min of exercise and a total dwell time of 6 min at 14,000 ft (Table 2). Table 3 shows the rapid resaturation of several subjects resting at 14,000 ft following mask donning and subsequent maintenance of saturation during exercise. The average blood oxygen saturations at 20,000 ft reading and exercising were slightly higher than the ground-level baseline controls (Table 4). In Table 5 the average calculated tracheal partial pressures of approximately 160-169 mmHg were also higher than the 140-mm breathing air at ground level (Oklahoma City). In Table 6 nitrogen values measured simultaneously in the bag and mask facepiece emphasize the very large fluctuation of gas composition occurring in a diluter rebreathing mask with each breath. This table also provides an estimation of the existence and extent of expired gas entering the rebreathing bag.

Examining Table 7 one may note that the average blood oxygen saturations at 25,000 ft were slightly in excess of the average ground-level control.

The calculated inspired oxygen partial pressures at 25,000 ft (Table 8) ranging from 139.6 to 145.5 mmHg are equivalent to slightly in excess of the ground air breathing oxygen partial pressure of 140 mmHg. In Table 9 one may note that the concentration of nitrogen measured in the rebreather bag at 25,000 ft is reduced when compared to 20,000 ft.

The average blood oxygen saturation at 30,000 ft (Table 10) indicates only a slight reduction. However, several individual subjects indicated a significant reduction to 87-89 percent saturation. Heart rates and respiration were also elevated slightly above corresponding measurements at 25,000 and 20,000 ft. Calculated average inspired tracheal oxygen partial pressures ranging from 114 to 122 are consistent with the average blood oxygen saturation readings (Table 11).

Subject JV, who exhibited a low blood oxygen saturation (87-89%) (Table 10), also exhibited a low inspired oxygen partial pressure (100 mm - 98 mm). One female subject's saturation dropped to approximately 91 percent with a corresponding drop of the inspired tracheal oxygen partial pressure to 102-97 mm.

Although the saturation of subject JH dropped to 89 percent, the tracheal partial pressure was calculated at 120 mm.

In Table 12 one may note a further reduction of nitrogen in the rebreather bag.

After descent to ground level, the mask was left on six of the subjects and determinations were made of the carbon dioxide in the mask facepiece and rebreather bag. The recording of blood oxygen saturation, heart rates, and respiration were continued and are shown in Table 13.

The 3-min periods of reading at each altitude were recorded on an Ampex recorder and later evaluated in terms of volume and clarity (Table 15). During reading the subjects' speech intelligibility was generally quite good. That few of the subjects did not talk directly into the microphone resulted in some compromise of clarity and the mask appeared to produce a slight muffled effect in some instances.

Measurements of carbon dioxide content of the mask facepiece and rebreather bag are shown in Table 14. With the exception of subject DR, maximums of 3 and 5 percent carbon dioxide were detected in the rebreathing bag and mask facepiece respectively. The 5-percent maximum value, approximating an end expiratory sample, is equal to 34 mm of partial pressure, somewhat less than that of the normal 40 mm partial pressure of end expiratory gas composition. Subject DR, a SCUBA diver, exhibited a tendency to skip breathe, a technique habitually used by some divers to conserve air. This subject's respiration during the carbon dioxide determination was so shallow and irregular that a meaningful impedance pneumograph recording was unobtainable. This subject showed a maximum carbon dioxide level of 8.9 percent in the rebreather bag. However, it is felt that the carbon dioxide measurements at ground level do not indicate a problem at altitude with the increased flow and ventilation due to gaseous expansion of the supply oxygen at altitude.

For example, at 20,000 ft, the 2.7-L/min flow STPD ground level would equal approximately 7.5 BTPS. In addition, a concentration of approximately 14 percent carbon dioxide would be required to produce an inspired partial pressure of 40 mmHg at 20,000 ft (4,5). At ground level 5.8 percent carbon dioxide produces an inspired 40 mmHg partial pressure. In evaluating carbon dioxide concentration one is again faced with a nonhomogeneous mixture of gases in the mask and rebreather bag. The end expiratory carbon dioxide concentration appears to be the more reliable measure because it reflects conditions in the lungs.

Review of Table 14 indicates the average carbon dioxide maximum values to be lower than expected, approaching in some

instances that expected for mixed expired gas. Therefore, it is doubtful that measurements of carbon dioxide in the mask face-piece provided consistently the degree of accuracy required for precise determinations of the end expiratory carbon dioxide.

Rebreathing of excessive carbon dioxide concentrations should have produced a significant change in respiration and heart rates. Examination of Table 13 indicates no such effects.

Inspired concentrations of carbon dioxide of up to 2 percent have been shown to have little or no physiological effect (5).

Two additional chamber flights were made with two current types of rebreathing masks using subjects BH and DZ, who also participated as subjects in the first series.

In Table 16 the results are shown for subject BH wearing the Zep-Aro (Cessna Part No. C 166009-0401) mask equipped with a mask-mounted microphone. At 30,000 ft, saturation during exercise dropped lower than the 14,000-ft baseline and the equivalent previous test wearing the Cessna mask. Resaturation was not subsequently accomplished during reading as in the previous evaluation. Calculated inspired oxygen partial pressures ranged from 93 mmHg to 102 mmHg (Table 17).

Results of subject DZ wearing the K-S mask are shown in Table 18. Saturation dropped to 91 percent at 25,000 ft during exercise but was reestablished during subsequent reading. At 30,000 ft, saturation dropped during exercise to 84.8 percent, lower than the 14,000-ft baseline, but was again reestablished during reading. During the previous test the saturation of subject DZ wearing the Cessna mask showed no indication of reduction at 25,000 ft during exercise. At 30,000 ft, there was some reduction in saturation with the Cessna mask during exercise but not of the magnitude experienced with the K-S mask. Calculated inspired tracheal oxygen partial pressures of 98-102 mmHg (Table 19) are consistent with the blood oxygen saturations obtained.

In Phase 2 the Cessna mask was evaluated during extended-duration chamber flights at altitudes of 25,000 and 30,000 ft. Longer periods of exercise and rest were utilized, and the resting condition was substituted for reading. Table 20 presents the blood oxygen saturation, heart rate, and respiration of subject DD during two 1-h flights at 25,000 ft. The second flight varied from the first only in that the oxygen supply pressure was reduced to 60 psi.

Blood oxygen saturation remained above the air-breathing ground-level control at all times during the flights. Inspired tracheal oxygen partial pressures were generally above that for

breathing air at ground level (Table 21). An extended-duration chamber flight to 30,000 ft was conducted with subject JV. At the end of 6 min of light exercise following 16 min dwell time at 30,000 ft, the subject's blood saturation had dropped to 83 percent. At the end of the 24th min at 30,000 ft during resting the oxygen supply pressure was reduced from 70 psi to 60 psi. Light exercise was initiated at the end of the 27th min and by the 32nd min the blood oxygen saturation had dropped to 75 percent. At this point the remainder of the flight was aborted as a precautionary measure, not only because of the subject's deteriorating condition, but also because of development of moderate symptoms of bends by the safety observer, which could only be aggravated by further dwell at this altitude. Table 23 reflects the calculated inspired oxygen partial pressure.

In the third phase two exploratory flights were conducted simultaneously to measure end expiratory nitrogen in the nostrils and mask facepiece and, hopefully, to correlate these two sampling locales and determine their relationship.

The first of these flights consisted of a 12-min dwell time at 25,000 ft with the subject engaged in 6 min of resting and 6 min of exercising. The chamber then ascended to 30,000 ft, at which time the rest-exercise cycle was repeated. As in the previous extended-duration flights, subject DD maintained good blood oxygen saturation (Table 24). Review of the calculated inspired oxygen concentrations indicates that readings from the mask vary by only 2 to 3 percent from those in the nostrils (Table 25). Figure 4 is a reproduction of the nitralyzer record during exercise at 30,000 ft.

The second of these two flight profiles was identical to the first except ascent was to 27,500 and 30,000 ft instead of 25,000 and 30,000 ft. Blood saturations of subject BH resting at 27,500 ft were equal to or higher than the ground-level control, dropping only slightly below the ground-level control during exercise. However, at 30,000 ft with light exercise, saturation dropped to 89 percent.

The calculated inspired oxygen concentration as derived from nitrogen recordings in the mask and nostrils indicates a variation of 2 to 4 percent at altitudes of 27,500 and 30,000 ft (Table 27). Variation was as much as 5 percent at 14,000 ft. The mask, however, had been donned only shortly before these readings were taken. The subject was previously breathing air at 14,000 ft and, as a result, readings were more variable because a steady state had not been attained.

IV. Discussion.

In the selection of an oxygen system, one must consider a number of factors: environment and altitude, aircraft characteristics, flight mission, and the wearer's knowledge and training relative to oxygen requirements and equipment. For example, a diluter type of mask that may be satisfactory in providing protection under steady-state conditions at a given altitude may not provide adequate protection following rapid decompression to the same altitude. All evaluations conducted in this study were based on the assumption of mask utilization in unpressurized aircraft.

Several comments should be made relative to the physiological variability of the subjects and the limitations of the measurements.

It was noted that when subjects were at 14,000 ft, breathing air and resting, the oximeter would vary considerably in response to changes in respiration. This fluctuation or hunting at times would amount to 4- to 5-percent saturation in response to a particularly deep respiration following a relatively long period of shallow and irregular breathing. After the mask was donned and resaturation established, this fluctuation during reading reduced considerably and the subject exhibited maximal stability during exercise. Evaluation during reading was carried out because of the possible effect on dilution of high inspiratory flows characteristic of speech. In addition it is not uncommon for the pilot and passengers of unpressurized light private aircraft to engage in conversation. A third reason for the reading was to evaluate speech intelligibility and the possible effect of the mask on aircraft-to-traffic-control communication. The differences between respiration during exercise and reading are shown in Figures 2 and 3.

Short periods of voluntary hyperventilation have been used in the past to evaluate the effect on mask efficiency of changes in respiration induced by emotional factors. However, it is practically impossible for a sedentary subject to maintain voluntary hyperventilation for more than 2 to 3 min without experiencing severe symptoms of hypocapnia (dizziness, paresthesia, muscle cramps, etc.). Drastic changes in blood chemistry and cerebral blood flow also detract from the use of voluntary hyperventilation in mask evaluation.

In lieu of voluntary hyperventilation a light exercise was used to stimulate respiration and concurrently simulate light physical activity as compared to complete sedentary resting conditions. It is admitted that exercise will produce an increase in oxygen consumption, but at the level utilized in this study this would approximate only 0.3 to 0.4 L/min above the resting level.

Unless carefully studied, interpretation of the nitralyzer recordings from a diluter-type mask can be misleading. One must keep in mind that these recordings represent changes in gas composition and not necessarily volumes or respiratory excursions. A line is drawn through the end expiratory points in Figures 4 and 5. In Figure 4, taken after 1 min of exercise at 30,000 ft, there is still a slight upward slope, indicating a slow increase in concentration of nitrogen being introduced into the mask. In Figure 4, after 5 min of exercise at 30,000 ft, the end expiratory nitrogen appears to have stabilized.

The height and weight of subjects may have affected some of the evaluations because oxygen consumption is directly related to the body surface areas. Subject JV, at a weight of 197 lb, was the largest subject evaluated. He experienced a low blood oxygen saturation during the first phase of the evaluation at 30,000 ft. During the extended flight at 30,000 ft, he again experienced a low blood oxygen saturation at an oxygen supply pressure of 70 psi. When the pressure was cut to 60 psi, the saturation dropped precipitously and a descent was initiated. Subject DD, a small male subject weighing 135 lb, completed two 1-h flights at 25,000 ft, using oxygen supply pressures of 70 psi and 60 psi without a significant reduction in blood oxygen saturation. In a third evaluation, after 6 min of exercise at 30,000 ft, this subject's saturation only dropped to 94 percent compared to 83 percent for subject JV.

Control of respiration in individuals who are not acclimatized to altitudes, such as in the Andes Mountains, is primarily regulated by a delicate balance of carbon dioxide partial pressure in the lungs and its effect on the blood. Regulatory receptors in the central nervous and circulatory systems are in turn affected via the blood.

Oxygen lack does not play a part in increasing respiration until an equivalent altitude of 10,000 to 12,000 ft is reached, at which point hypoxic drive of respiration becomes a factor. If a significant degree of hypoxia becomes established, a vicious cycle caused by using a diluter-type mask may develop in that the mask wearer may reflexly hyperventilate in response to hypoxia. The increased ventilation during hyperventilation results in more ambient air being drawn into the mask, diluting the oxygen and resulting in decreased mask efficiency. The dilution of oxygen in turn results in increased hypoxia. At an altitude of 25,000 ft the Cessna mask with the Zep-Aro orifice delivering 2.7 L/min produced an average blood oxygen saturation equal to or in excess of the ground-level controls. At 27,500 ft the blood oxygen saturation of the one subject evaluated at this altitude was only slightly lower than the ground-level control. At 30,000 ft several of the subjects experienced saturations below 90 percent that during

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one extended-duration flight dropped to 83 percent at 70 psi and 75 percent when the supply pressure was reduced to 60 psi.

It must be realized that these tests were carried out under laboratory conditions with masks of the proper size and correctly donned. Under actual conditions of use, care and caution may not be as ideal.

The data indicate that flows to the mask should be increased for altitudes above 25,000 ft. Above 28,000 to 30,000 ft a much safer alternative is to use a nondiluting mask supplied with an adequate flow to insure 100 percen. cxygen.

Probably the largest amount of experience relative to the occurrence of hypoxia at altitudes of 25,000 to 30,000 ft was gained by the Army Air Corps in World War II in B-24 and B-17 aircraft. Hypoxic incidents were four times more frequent in the B-17s operating at an average altitude of 25,000 ft than in the B-24s operating at an average altitude of 22,000 ft. The average highest altitude for the B-24 was 25,000 ft; for the B-17, 30,000 ft.

The Army Air Corps reported 10,700 cases of hypoxia resulting in unconsciousness and 110 deaths during World War II operations.

In addition to hypoxia at flight altitudes of 25,000 to 30,000 ft, in unpressurized aircraft there is the problem of dysbarism or effect of reduced pressures on the body exclusive of hypoxia. The literature is so extensive in this area that it will not be referenced in this report. However, the altitude range of 25,000 to 30,000 ft is considered a critical area in which bends are likely to develop in as little as 15 to 30 min. Obesity is a predisposing factor and deaths have been reported as low as 22,000 ft (6).

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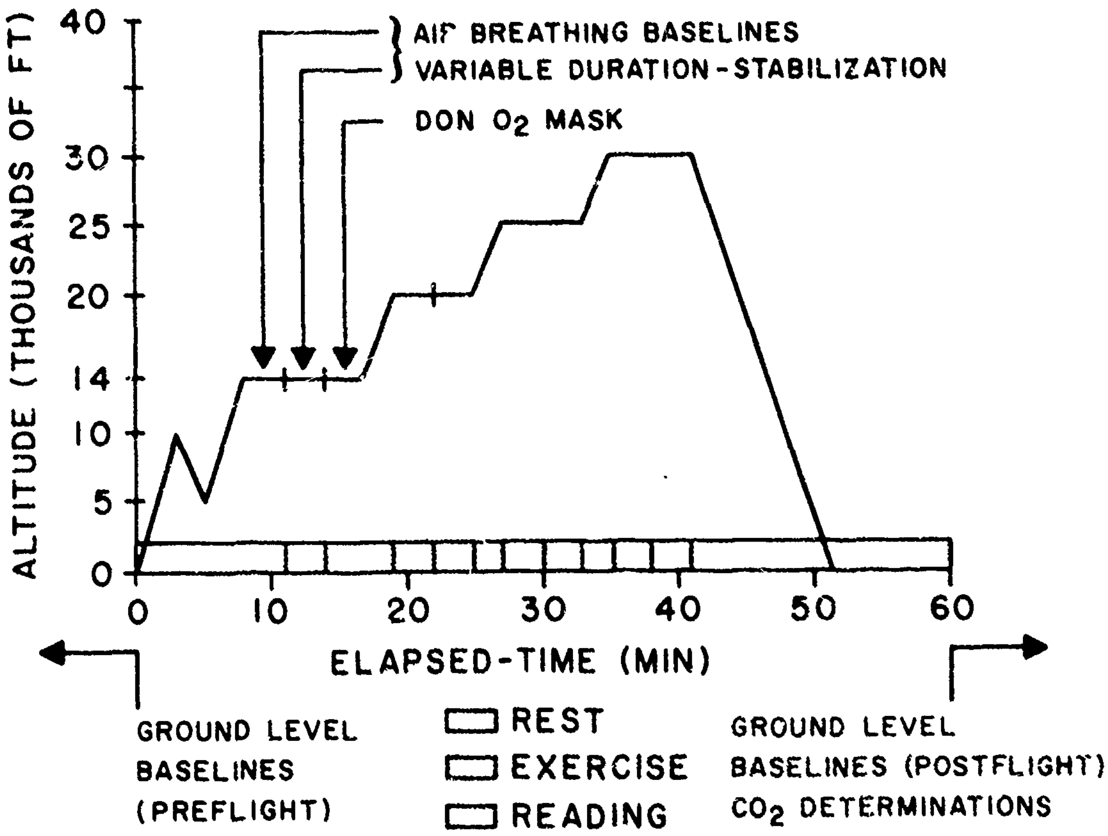

FIGURE 1. Altitude chamber flight profile and subject activity of 10 subjects wearing the Cessna mask.

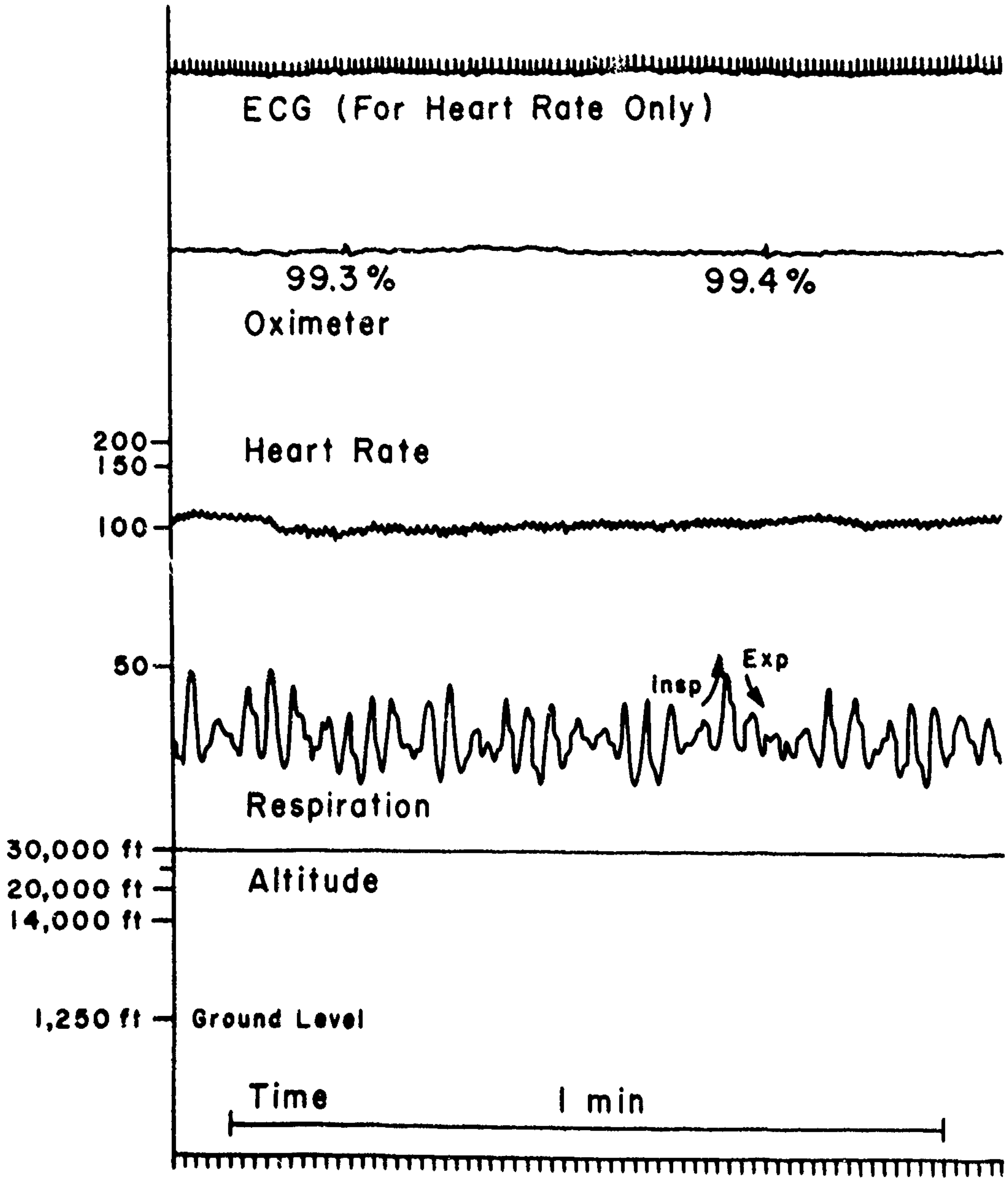

FIGURE 2. Blood oxygen saturation, heart rates, and respiration of subject DM at 30,000 feet wearing the Cessna mask. Second minute of exercise. Note the stabilization of heart rate.

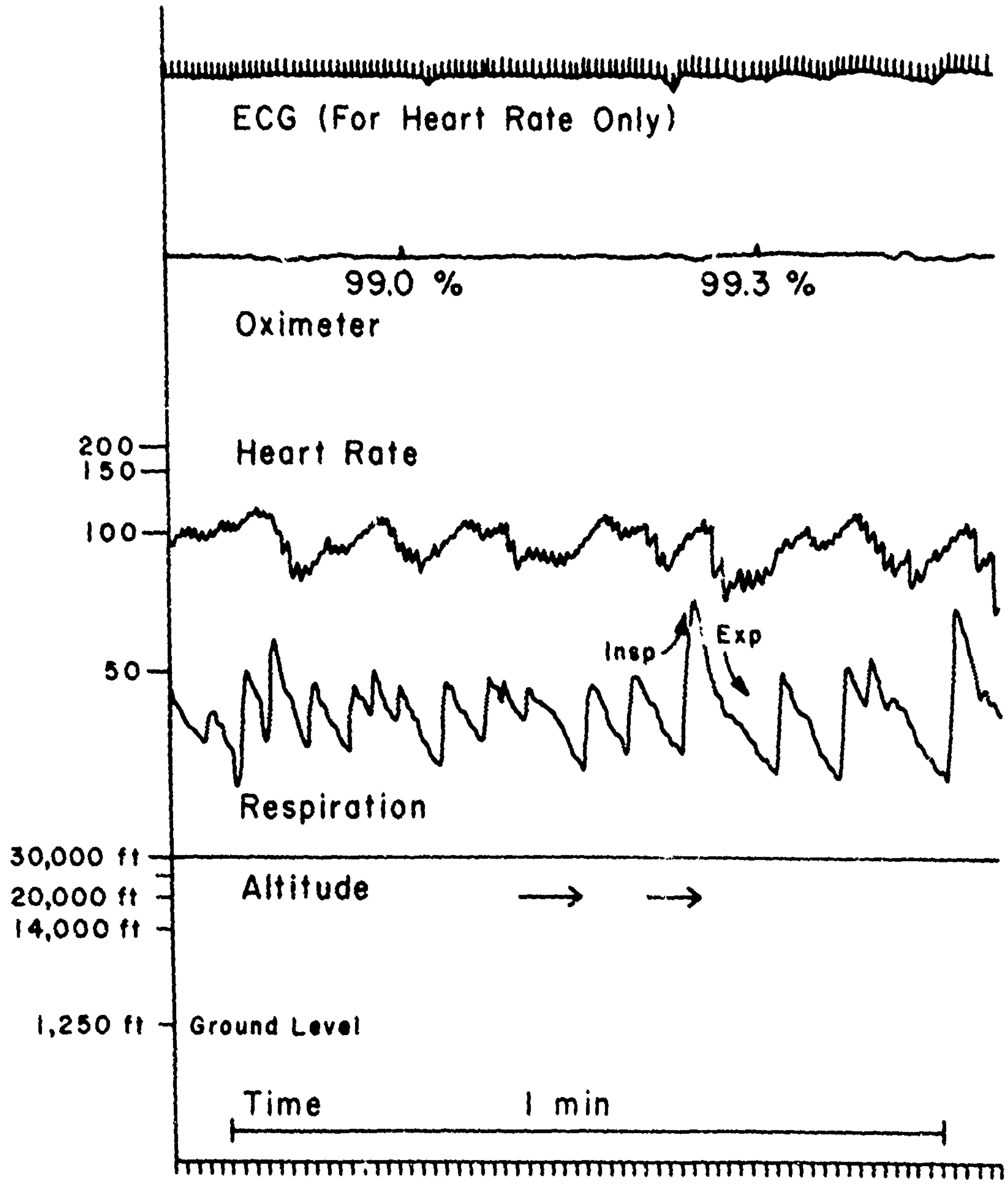

FIGURE 3. Blood oxygen saturation, heart rate, and respiration of subject DM at 30,000 feet wearing the Cessna mask. Second minute of reading. Note the rapid inspiratory excursions of the chest characteristic of speech. Normal fluctuation of heart rate with respiration is evident.

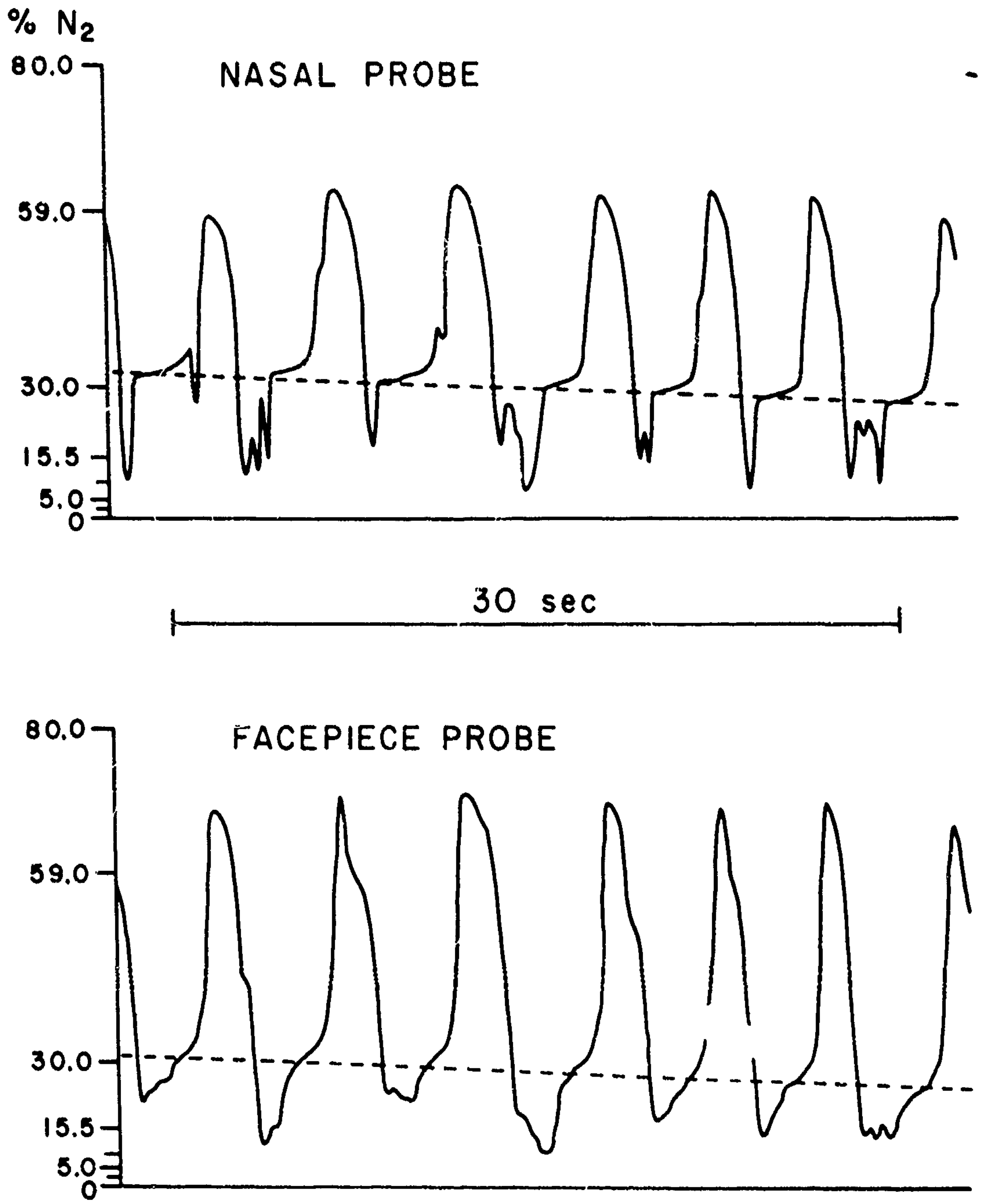

FIGURE 4. Simultaneous measurement of nitrogen by probes inserted in nostril and the Cessna mask facepiece. A dashed line is drawn through the end expiratory points. Subject DD. First minute of exercise at 30,000 feet. The slope indicates the increase in end expiratory nitrogen during transition from resting to exercise. Recording must be read from right to left.

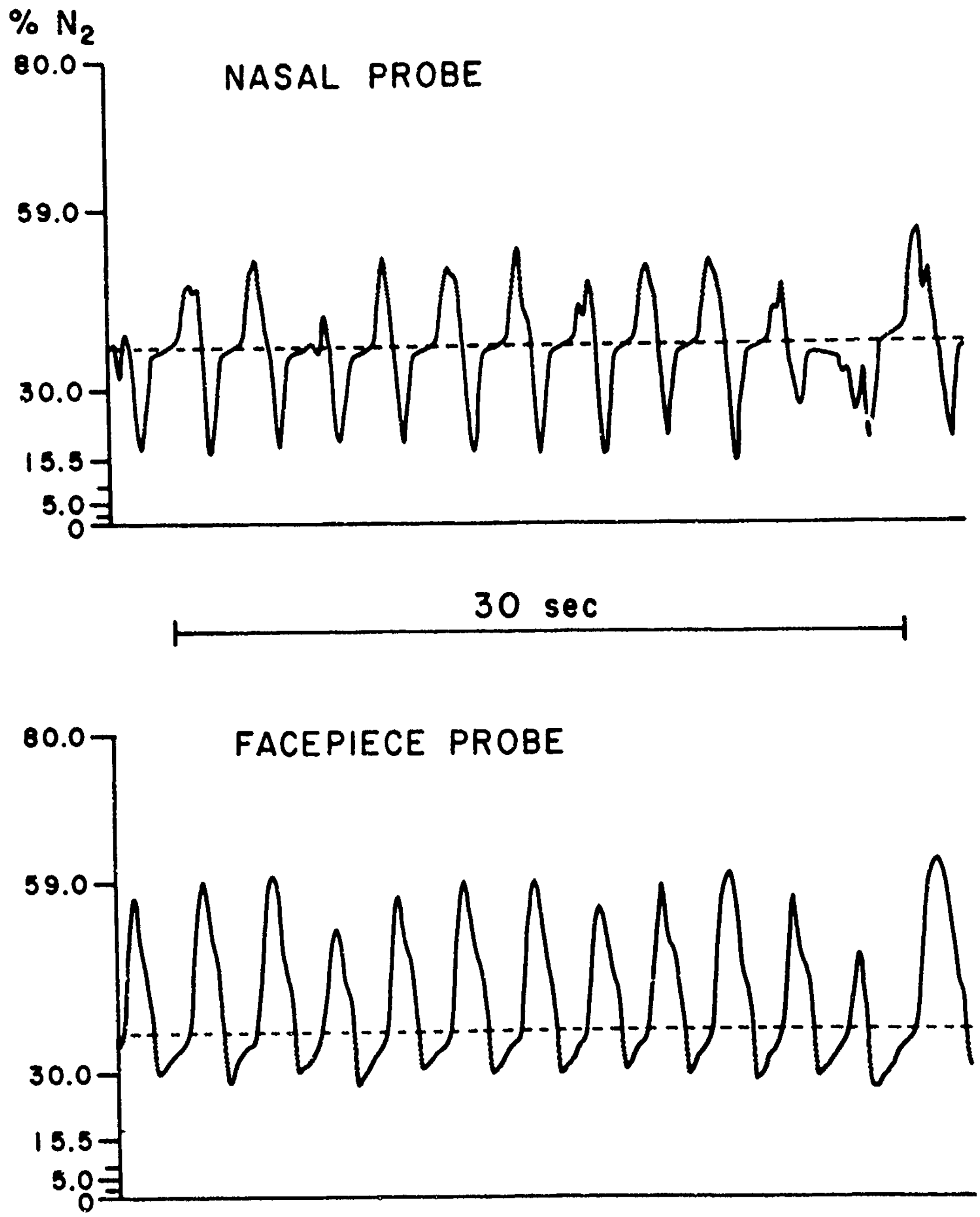

FIGURE 5. Simultaneous measurement of nitrogen by probes inserted in nostril and the Cessna mask facepiece. A dashed line is drawn through the end expiratory points. Subject BH. Fifth minute of exercise at 30,000 feet. Recording must be read from right to left.

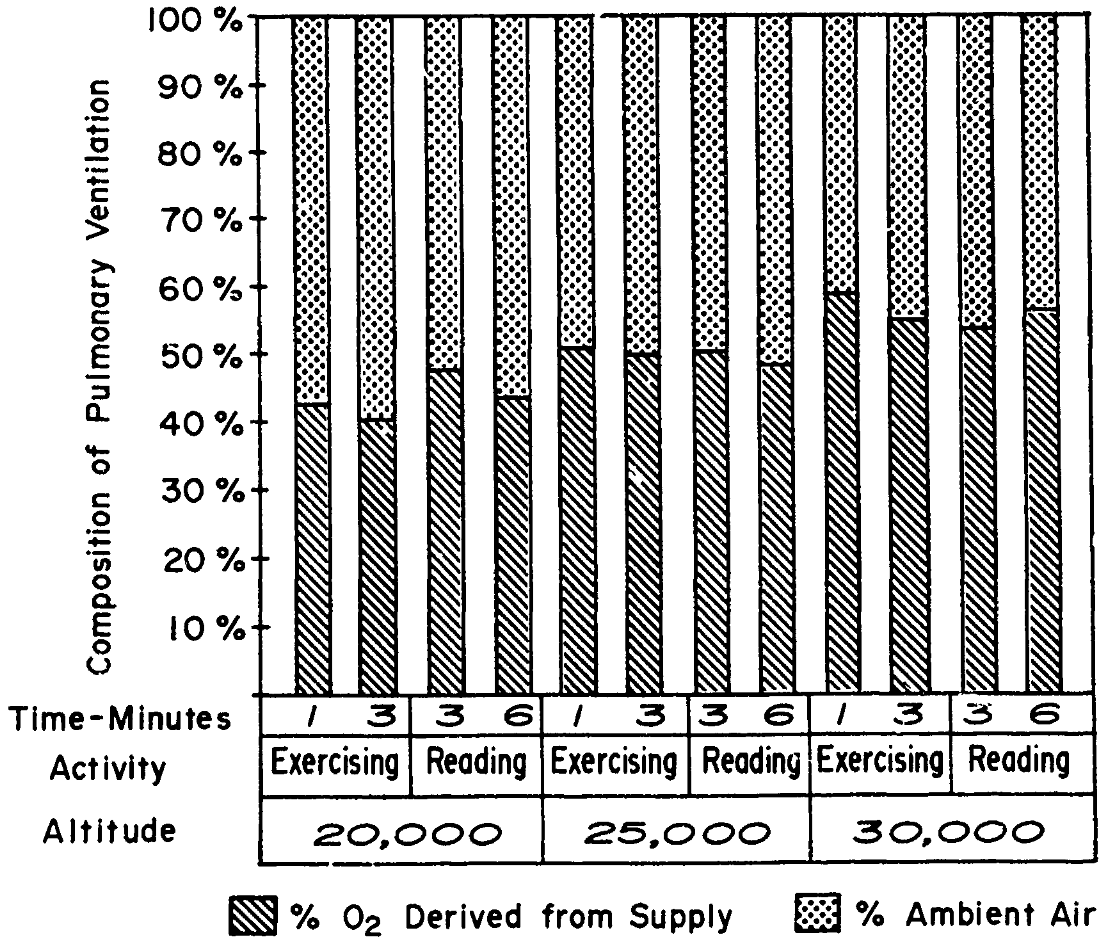

FIGURE 6. Histograph showing dilution of inspired gas with ambient air as calculated from the end expiratory nitrogen concentration. Subjects exercising and reading at 20,000, 25,000, and 30,000 feet while wearing the Cessna mask.

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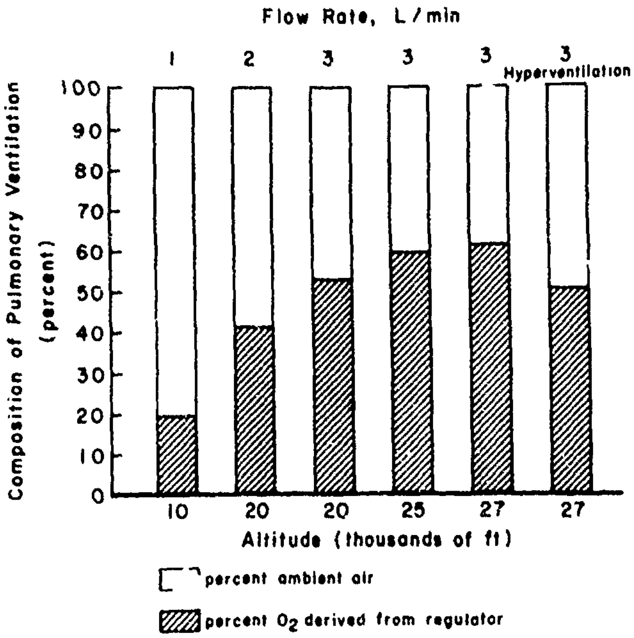

FIGURE 7. Luft's histograph showing dilution of inspired gas with ambient air at different altitudes and rates of flow during evaluation of the K-S mask in 1961.

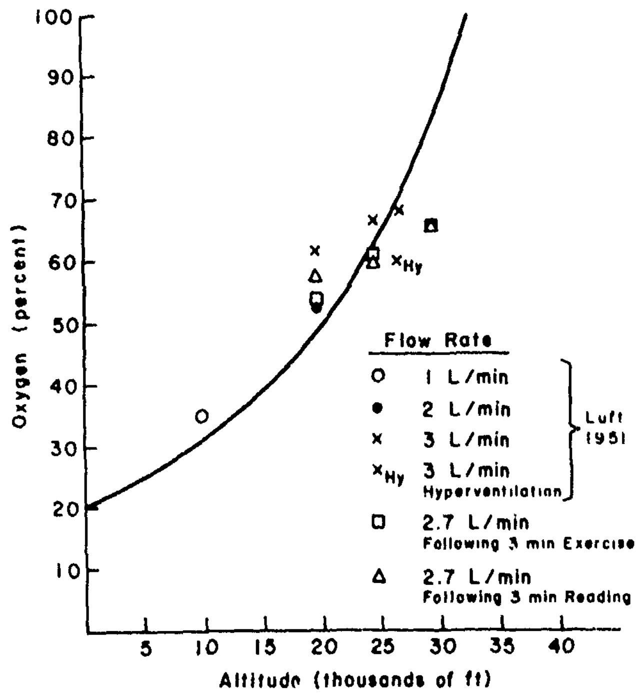

FIGURE 8. Concentration of inspired gas using the Cessna mask superimposed over Luft's plot of the K-S mask in 1951. Oxygen flow controlled by a Zep-Aro orifice F 365-1080-2 with a flow of 2.7 L/min at a pressure of 70 psi. Curve represents inspired oxygen required to theoretically maintain sea-level conditions.

TABLE 1. Blood Oxygen Saturation, and Heart and Respiratory Rate Baselines of Subjects at Ground Level Breathing Air at Rest Immediately Prior to Ascent to Altitude

N = 10

Subject	Sex	Oximeter (percent)	Heart Rate	Respiratory Rate	Age (yr)	Height (in)	Weight (lb)
DR	M	100.0	88	--	34	71.5	184
JT	M	99.0	75	12	37	71.0	155
JH	F	98.4	100	17	36	66.5	135
MZ	F	97.0	76	15	43	64.0	115
LZ	F	95.6	100	11	15	62.0	110
DM	F	97.0	90	23	33	64.0	115
GF	M	95.0	94	22	33	68.5	130
BH	M	96.8	78	14	30	71.0	168
JV	M	95.6	78	14	44	68.0	197
DZ	M	96.0	82	9	44	68.0	180
Range		95-100	75-100	9-23			
Mean		97.0	86	15			

TABLE 2. Blood Oxygen Saturation, and Heart and Respiratory Rate Baselines of Subjects Breathing Air at 14,000 ft, Resting and Exercising. Inspired Tracheal Oxygen Partial Pressure 83.8 mmHg

Resting, First and Third Minutes at 14,000 ft
N = 9*

Subject	Sex	Oximeter Percent		Heart Rate		Respiratory Rate	
		Minute		Minute		Minute	
		1	3	1	3	1	3
DR	M	---	---	--	--	---	---
JT	M	96.0	91.0	80	78	---	---
JH	F	93.0	93.5	108	102	19	19
MZ	F	93.6	95.3	78	80	12	14
LZ	F	91.5	92.8	96	90	15	20
DM	F	94.0	92.5	90	93	18	17
GF	M	90.4	92.0	100	100	17	19
BH	M	79.0	78.0	74	84	12	13
JV	M	89.5	90.1	84	85	16	---
DZ	M	92.0	93.0	88	88	11	10
Range		79.0-96.0	78.0-95.3	74-108	80-102	11-19	10-20
Mean		91.0	91.0	89	89	15	16

Exercising, Fourth and Sixth Minutes at 14,000 ft
N = 8*

Subject	Sex	4	6	4	6	4	6
DR	M	92.0	83.0	108	123	---	---
JT	M	---	---	--	--	---	---
JH	F	---	---	--	--	---	---
MZ	F	94.0	86.0	80	102	19	29
LZ	F	88.0	90.0	132	142	24	30
DM	F	92.0	93.0	114	120	26	28
GF	M	90.2	91.0	100	105	24	26
BH	M	76.0	72.0	92	94	20	17
JV	M	86.0	86.0	105	108	19	18
DZ	M	90.0	92.0	100	100	22	22
Range		76.0-94.0	72.0-93.0	80-132	94-142	19-26	17-30
Mean		88.5	86.6	104	112	22	24

*Number of subjects for whom data were obtained.

TABLE 3. Blood Oxygen Saturation, and Heart and Respiratory Rate Baselines of Several Subjects at 14,000 ft Wearing the Cessna Oxygen Mask and Breathing Oxygen With the Zep-Aro Orifice (F 365-1080-2)

Resting, Mask Donned Following Air Breathing at 14,000 ft
N = 3

		Oximeter Percent		Heart Rate		Respiratory Rate	
		Minute		Minute		Minute	
Subject	Sex	0	0.75	0	0.75	0	0.75
DR	M	83.0	98.5	95	80	--	--
JT	M	91.0	97.0	78	70	15	16
JH	F	93.5	97.0	102	115	19	18
Range		83.0-93.5	97.0-98.5	78-102	70-115	15-19	16-18
Mean		89.0	97.5	92	88	17	17

Exercising, Mask On at 14,000 ft
N = 2

		1	3	1	3	1	3
JT	M	98.0	97.5	70	75	19	21
JH	F	93.5	97.0	102	115	19	18
Range		93.5-98.0	97.0-97.5	70-102	75-115	19-19	18-21
Mean		95.8	97.2	86	95	19	19

TABLE 4. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subjects at 20,000 ft Wearing Cessna Mask With the Zep-Aro Orifice (F 365-1080-2) at an Oxygen Supply Pressure of 70 psi

N = 10

Exercising, First and Third Minutes at 20,000 ft

		Oximeter Percent		Heart Rate		Respiratory Rate	
		Minute		Minute		Minute	
Subject	Sex	1	3	1	3	1	3
DR	M	97.5	97.5	80	100	--	--
JT	M	97.6	97.4	70	80	21	19
JH	F	97.6	97.6	108	115	21	21
MZ	F	97.0	98.3	99	94	21	19
LZ	F	96.7	97.4	112	112	24	25
DM	F	99.4	99.4	105	108	25	26
GF	M	98.6	98.0	98	96	24	23
BH	M	98.4	98.7	74	74	18	17
JV	M	96.7	96.3	98	100	19	20
DZ	M	96.6	96.5	96	94	19	16
Range		96.6-99.4	96.3-99.4	70-112	74-115	18-25	16-26
Mean		97.6	97.7	94	97	21	21

Reading, Fourth and Sixth Minutes at 20,000 ft

		4	6	4	6	4	6
DR	M	97.5	100.0	100	90	12	10
JT	M	98.0	98.6	75	70	16	17
JH	F	97.5	98.0	105	110	16	15
MZ	F	98.3	98.3	87	84	13	10
LZ	F	97.8	98.0	98	98	17	13
DM	F	99.4	99.4	100	100	13	11
GF	M	98.2	99.2	100	100	20	16
BH	M	99.0	99.8	86	82	17	14
JV	M	97.3	97.8	88	87	15	14
DZ	M	97.9	98.8	96	94	14	13
Range		97.3-99.4	97.8-100.0	75-105	70-110	12-20	10-17
Mean		98.1	98.8	94	92	15	13

TABLE 5. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Cessna Mask at 20,000 ft as Derived From Estimates of End Expiratory Nitrogen

N = 10

Exercising, First and Third Minutes at 20,000 ft

		End Expiratory Nitrogen		Dilution Percent		Percent Oxygen from						Calculated $P_{T_{O_2}}$ mmHg	
						Supply		Ambient		Supply + Ambient			
		Minute		Minute		Minute		Minute		Minute		Minute	
Subject	Sex	1	3	1	3	1	3	1	3	1	3	1	3
DR	M	57	53	72	67	28	33	15	14	43	47	130	142
JT	M	43	40	54	51	46	49	11	11	57	60	172	181
JH	F	45	48	57	61	43	39	12	13	55	52	166	157
MZ	F	52	50	66	63	34	37	14	13	48	50	145	151
LZ	F	45	42	57	53	43	47	12	11	55	58	166	175
DM	F	47	42	60	53	40	47	13	11	53	58	160	175
GF	M	40	46	51	58	49	42	11	12	60	54	181	163
BH	M	43	47	54	60	46	40	11	13	57	53	172	160
JV	M	46	52	58	66	42	34	12	14	54	48	163	145
DZ	M	38	47	48	60	52	40	10	13	62	53	187	160
Mean		45.6	46.7	57.7	59.2	42.3	40.8	12.1	12.5	54.4	53.3	164.2	160.9

Reading, Fourth and Sixth Minutes at 20,000 ft

		4	6	4	6	4	6	4	6	4	6	4	6
DR	M	48	47	61	60	39	40	13	13	52	53	157	160
JT	M	39	37	49	47	51	53	10	10	61	63	184	190
JH	F	42	44	53	56	47	44	11	12	58	56	175	169
MZ	F	47	47	60	60	40	40	13	13	53	53	160	160
LZ	F	33	36	42	46	58	54	9	10	67	64	202	193
DM	F	47	42	60	53	40	47	12	11	53	58	160	175
GF	M	44	45	56	57	44	43	12	12	56	55	169	166
BH	M	46	46	58	58	42	42	12	12	54	54	163	163
JV	M	45	47	57	60	43	40	12	13	55	53	166	160
DZ	M	48	47	61	60	39	40	13	13	52	53	157	160
Mean		43.9	43.8	55.7	55.7	47.9	44.3	11.7	11.9	56.1	56.2	169.3	169.6

TABLE 6. Percentage of Nitrogen as Measured in the Mask Facepiece and Rebreathing Bag at 20,000 ft

N = 10

		Exercising First and Third Minutes at 20,000 ft						Reading Fourth and Sixth Minutes at 20,000 ft					
		Range		Peak		Mean		Range		Peak		Mean	
		Minute		Minute		Minute		Minute		Minute		Minute	
Subject	Location	1	3	1	3	1	3	4	6	4	6	4	6
DR	Bag	10-38	15-30	42	48	17	23	8-20	5-17	20	20	14	14
	Mask	43-65	45-68	67	70	54	57	37-59	38-59	69	66	47	51
JT	Bag	5-57	7-55	60	59	19	15	8-55	10-40	55	59	17	23
	Mask	35-55	34-57	64	61	45	47	35-61	35-52	61	57	47	43
JH	Bag	8-12	14-16	13	38	10	15	10-15	5- 5	28	15	13	5
	Mask	40-65	40-68	68	70	55	15	35-55	30-55	60	59	44	45
MZ	Bag	10-20	5-15	31	24	13	10	3-10	4- 8	12	10	6	6
	Mask	30-58	38-57	59	60	47	47	40-55	40-55	57	59	47	47
LZ	Bag	7-18	12-26	42	30	10	15	5-15	5-13	25	52	7	8
	Mask	30-59	35-65	68	68	45	52	20-55	25-55	57	68	38	36
DM	Bag	1- 3	1- 3	3	6	2	2	1- 4	1- 4	6	6	2	2
	Mask	12-67	16-67	68	74	43	45	22-65	15-67	65	68	47	44
GF	Bag	20-30	15-23	42	40	25	17	10-15	10-15	23	16	13	13
	Mask	40-65	40-59	[illegible]	62	53	50	43-56	45-57	58	60	50	52
BH	Bag	2-15	[illegible]-15	26	30	10	6	10-20	5-10	40	11	12	8
	Mask	35-65	35-62	68	63	52	48	43-61	43-61	65	70	52	52
JV	Bag	15-28	25-38	30	40	17	32	15-25	10-23	37	26	18	15
	Mask	42-63	48-64	67	65	52	55	42-53	35-58	54	59	45	47
DZ	Bag	5-20	10-23	25	25	14	17	13-23	13-25	25	26	16	16
	Mask	20-65	35-67	67	68	45	50	35-61	40-60	62	63	48	48

TABLE 7. blood Oxygen Saturation, and Heart and Respiratory Rates of Subjects at 25,000 ft Wearing Cessna Mask With the Zep-Aro Orifice (F 365-1080-2) at an Oxygen Supply Pressure of 70 psi

N = 10

Exercising, First and Third Minutes at 25,000 ft

		Oximeter Percent		Heart Rate		Respiratory Rate	
		Minute		Minute		Minute	
Subject	Sex	1	3	1	3	1	3
DR	M	99.0	97.5	85	105	--	--
JT	M	98.6	97.4	70	80	18	16
JH	F	98.3	98.3	108	108	22	22
MZ	F	97.8	98.2	92	100	23	27
LZ	F	97.8	97.3	118	118	23	26
DM	F	98.0	98.4	105	115	27	29
GF	M	99.4	99.4	98	98	25	22
BH	M	97.0	99.0	78	74	17	17
JV	M	95.8	95.2	100	100	22	21
DZ	M	96.8	97.5	96	94	18	16
Range		95.8-99.4	95.2-99.4	70-118	74-118	17-27	16-29
Mean		97.8	97.8	95	99.2	22	22

Reading, Fourth and Sixth Minutes at 25,000 ft

		4	6	4	6	4	6
DR	M	97.5	99.0	105	95	12	12
JT	M	97.4	98.4	75	78	21	15.5
JH	F	98.3	99.0	114	106	17	16
MZ	F	97.8	98.0	94	94	12	12
LZ	F	98.0	98.2	98	103	16	14
DM	F	98.9	98.8	96	94	12	12
GF	M	99.4	99.6	104	98	15	13
BH	M	99.3	99.4	84	88	17	15
JV	M	97.0	97.1	94	95	17	17
DZ	M	98.3	99.3	94	92	16	16
Range		97.0-99.4	97.1-99.6	75-114	78-106	12-21	12-17
Mean		98.2	98.7	95.8	94.3	15.5	14.2

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TABLE 8. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Cessna Mask at 25,000 ft as Derived From Estimates of End Expiratory Nitrogen

N = 10

Exercising, First and Third Minutes at 25,000 ft

		End Expiratory Nitrogen		Dilution Percent		Percent Oxygen from						Calculated $P_{T_{O_2}}$ mmHg	
						Supply		Ambient		Supply + Ambient			
		Minute		Minute		Minute		Minute		Minute		Minute	
Subject	Sex	1	3	1	3	1	3	1	3	1	3	1	3
DR	M	44	47	56	60	44	40	12	13	56	53	131	125
JT	M	35	38	44	48	56	52	9	10	65	62	153	146
JH	F	38	40	48	51	52	49	10	11	62	60	146	141
MZ	F	38	40	48	51	52	49	10	11	62	60	146	141
LZ	F	35	37	44	47	56	53	9	10	65	63	153	148
DM	F	26	28	33	35	67	65	7	7	74	72	174	169
GF	M	45	43	57	54	43	46	12	11	55	57	129	134
BH	M	40	33	51	42	49	58	11	9	60	67	141	158
JV	M	45	47	57	60	43	40	12	13	55	53	129	125
DZ	M	35	38	44	48	56	52	9	10	65	62	153	146
Mean		38.1	39.1	48.2	49.6	51.8	50.4	10.1	10.5	61.9	60.9	145.5	143.3

Reading, Fourth and Sixth Minutes at 25,000 ft

		4	6	4	6	4	6	4	6	4	6	4	6
DR	M	38	40	48	51	52	49	10	11	62	60	146	141
JT	M	40	43	51	54	49	46	11	11	60	57	141	134
JH	F	41	45	52	57	48	43	11	12	59	55	139	129
MZ	F	42	42	53	53	47	47	11	11	58	58	136	136
LZ	F	37	35	47	44	53	56	10	9	63	65	148	153
DM	F	27	37	34	47	66	53	7	10	73	63	171	148
GF	M	40	40	51	51	49	49	11	11	60	60	141	141
BH	M	43	41	54	52	46	48	11	11	57	59	134	139
JV	M	42	40	53	51	47	49	11	11	58	60	137	141
DZ	M	43	43	54	54	46	46	11	11	57	57	134	134
Mean		39.3	40.6	49.7	51.4	50.3	48.6	10.4	10.8	60.7	59.4	142.7	139.6

TABLE 9. Percentage of Nitrogen as Measured in the Mask Facepiece and Rebreathing Bag at 25,000 ft

N = 10

		Exercising First and Third Minutes at 25,000 ft						Reading Fourth and Sixth Minutes at 25,000 ft					
		Range Minute		Peak Minute		Mean Minute		Range Minute		Peak Minute		Mean Minute	
Subject	Location	1	3	1	3	1	3	4	6	4	6	4	6
DR	Bag	12-20	15-28	41	38	16	21	5-14	5-20	16	20	8	10
	Mask	35-62	40-63	67	68	49	51	32-55	35-55	67	65	37	40
JT	Bag	5-40	6-40	50	46	14	14	6-40	2-30	60	43	18	14
	Mask	26-55	25-60	63	61	44	35	30-55	33-57	59	60	37	46
JH	Bag	3-10	10-10	25	10	5	10	5-10	5-10	20	17	8	8
	Mask	25-64	35-66	65	68	45	53	35-55	35-53	57	60	45	42
MZ	Bag	2- 6	2- 2	9	2	3	2	3-10	3- 3	10	5	5	3
	Mask	25-55	25-55	57	59	43	42	35-55	36-53	56	59	45	46
LZ	Bag	2- 8	2-16	10	17	3	3	5-15	5-10	23	17	6	6
	Mask	23-59	28-62	66	65	42	45	22-50	25-50	63	55	40	38
DM	Bag	0- 1	0- 0	1	0	0.2	0	0- 2	0- 3	6	3	2	2
	Mask	14-57	17-62	60	74	38	45	18-57	17-62	59	64	42	44
GF	Bag	7-14	16-30	38	37	12	23	9-27	6-18	46	37	13	11
	Mask	30-59	38-63	64	65	45	47	35-55	35-55	57	64	45	45
BH	Bag	2- 3	3- 3	8	3	3	3	5-13	2- 6	14	8	10	4
	Mask	31-61	25-60	67	65	48	44	38-62	38-60	65	66	48	50
JV	Bag	5-10	5-15	23	31	8	10	10-23	5-15	25	30	15	12
	Mask	40-65	45-65	67	67	54	54	38-54	35-55	57	57	46	45
DZ	Bag	7-15	8-19	24	23	11	13	13-18	9-14	23	15	15	12
	Mask	20-64	25-65	67	68	44	45	35-56	35-60	59	61	45	45

TABLE 10. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subjects at 30,000 ft Wearing Cessna Mask With the Zep-Aro Orifice (F 365-1080-2) at an Oxygen Supply Pressure of 70 psi

N = 10

Exercising, First and Third Minutes at 30,000 ft

		Oximeter Percent		Heart Rate		Respiratory Rate	
		Minute		Minute		Minute	
Subject	Sex	1	3	1	3	1	3
DR	M	98.0	94.5	90	105	--	--
JT	M	98.4	97.6	70	82	18	19
JH	F	98.5	98.6	108	112	21	21
MZ	F	95.8	92.0	103	122	15	20
LZ	F	97.0	96.8	112	115	27	26
DM	F	98.5	97.3	105	115	26	27
GF	M	99.4	99.3	100	100	23	24
BH	M	94.5	89.0	90	88	16	20
JV	M	87.0	89.0	104	104	19	22
DZ	M	97.4	93.4	94	96	17	19
Range		87.0-99.4	89.0-99.3	70-112	82-122	15-27	19-27
Mean		96.4	94.7	98	104	25	22

Reading, Fourth and Sixth Minutes at 30,000 ft

Subject	Sex	4	6	4	6	4	6
DR	M	96.5	98.0	105	90	13	18
JT	M	97.5	98.6	82	75	18	19
JH	F	98.3	99.0	116	108	16	21
MZ	F	91.0	95.0	112	118	20	16
LZ	F	97.0	97.4	104	100	11	13
DM	F	98.0	97.2	100	100	18	18
GF	M	99.0	99.4	100	98	11	12
BH	M	92.0	99.0	90	90	17	17
JV	M	93.0	95.0	87	86	19	17
DZ	M	97.8	98.4	96	96	20	19
Range		91.0-99.0	95.0-99.4	82-116	75-118	11-20	12-21
Mean		96.0	97.7	99.2	96.1	16	17

TABLE 11. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Cessna Mask at 30,000 ft as Derived From Estimates of End Expiratory Nitrogen

N = 10

Exercising, First and Third Minutes at 30,000 ft

Subject	Sex	End Expiratory Nitrogen Minute 1	3	Dilution Percent Minute 1	3	Percent Oxygen from Supply Minute 1	3	Percent Oxygen from Ambient Minute 1	3	Percent Oxygen from Supply + Ambient Minute 1	3	Calculated $P_{T_{O_2}}$ mmHg Minute 1	3
DR	M	37	40	47	51	53	49	10	11	63	60	113	107
JT	M	25	32	32	41	68	59	7	9	75	68	134	122
JH	F	37	35	47	44	53	56	10	9	63	65	113	116
MZ	F	41	43	52	54	48	46	11	11	59	57	106	102
LZ	F	30	27	38	34	62	66	8	7	70	73	125	131
DM	F	15	18	19	23	81	77	4	5	85	82	152	147
GF	M	28	35	35	44	65	56	7	9	72	65	129	116
BH	M	35	33	44	42	56	58	9	9	65	67	116	120
JV	M	44	45	56	57	44	43	12	12	56	55	100	98
DZ	M	28	43	35	53	65	47	7	11	72	58	129	104
Mean		32.0	35.1	40.5	44.3	59.5	55.7	8.5	9.3	68.0	65.0	121.7	116.3

Reading, Fourth and Sixth Minutes at 30,000 ft

Subject	Sex	4	6	4	6	4	6	4	6	4	6	4	6
DR	M	35	37	44	47	56	53	9	10	65	63	116	113
JT	M	35	35	44	44	56	56	9	9	65	65	116	116
JH	F	37	34	47	43	53	57	10	9	63	66	113	118
MZ	F	46	42	58	53	42	47	12	11	54	58	97	104
LZ	F	32	21	41	27	59	73	9	6	68	79	122	141
DM	F	25	26	32	33	68	67	7	7	75	74	134	133
GF	M	38	42	48	53	52	47	10	11	62	58	111	104
BH	M	43	37	54	47	46	53	11	10	57	63	102	113
JV	M	38	37	48	47	52	53	10	10	62	63	111	113
DZ	M	35	35	44	44	56	56	9	9	65	65	116	116
Mean		36.4	34.6	46.0	43.8	54.0	56.2	9.6	9.2	63.6	65.4	113.8	117.1

TABLE 12. Percentage of Nitrogen as Measured in the Mask Facepiece and Rebreathing Bag at 30,000 ft

N = 10

		Exercising: First and Third Minutes at 30,000 ft						Reading: Fourth and Sixth Minutes at 30,000 ft					
		Range		Peak		Mean		Range		Peak		Mean	
		Minute		Minute		Minute		Minute		Minute		Minute	
Subject	Location	1	3	1	3	1	3	4	6	4	6	4	6
DR	Bag	10-15	10-16	23	23	15	14	4-14	6-11	15	11	9	9
	Mask	30-60	32-65	67	67	47	50	25-43	28-42	59	58	35	33
JT	Bag	5-40	5-40	40	50	10	10	5-30	5-35	45	45	15	14
	Mask	18-44	22-62	50	64	30	43	27-53	22-52	59	57	42	35
JH	Bag	1- 5	5-12	6	28	3	8	5-10	5-10	15	22	8	7
	Mask	25-60	30-60	63	65	45	46	28-55	35-55	63	58	40	45
MZ	Bag	1- 1	1- 1	1	1	1	1	3- 4	2- 2	5	2	3	2
	Mask	33-61	37-63	64	65	48	50	39-59	38-57	62	62	48	47
LZ	Bag	1- 3	1- 2	11	3	2	1.5	2- 5	2-10	27	29	3	4
	Mask	14-57	15-57	65	70	35	35	15-55	15-50	65	59	30	32
DM	Bag	0- 0	0- 2	0	3	0	1	0- 1	0- 0	1	0	0.5	0
	Mask	10-58	14-58	60	69	37	40	15-56	13-57	57	59	39	40
GF	Bag	5-13	5-10	15	23	7	6	5-20	4- 8	35	24	10	7
	Mask	26-61	25-54	62	56	42	38	38-55	38-62	59	62	45	48
BH	Bag	4-10	2- 2	10	2	7	2	3-10	5-10	13	13	5	8
	Mask	30-60	25-60	66	63	45	45	32-61	30-50	63	57	45	40
JV	Bag	4-10	4- 6	17	6	6	5	5-15	10-15	30	47	10	12
	Mask	40-58	42-58	60	61	50	48	35-50	35-52	64	55	42	42
DZ	Bag	3-10	6-25	13	33	7	15	9-15	10-13	23	15	12	11
	Mask	8-59	12-62	62	65	32	35	30-55	30-53	61	56	43	42

TABLE 13. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subjects Resting at Ground Level, Postflight, Wearing Cessna Mask With Zep-Aro Orifice (F 365-1080-2) at an Oxygen Supply Pressure of 70 psi

N = 6

		Oximeter Percent		Heart Rate		Respiratory Rate	
		Minute		Minute		Minute	
Subject	Sex	1	3	1	3	1	3
DR	M	99.5	99.5	76	72	--	--
JT	M	99.5	99.6	60	62	--	--
JH	F	100.5	100.5	81	81	18	16
BH	M	97.7	97.7	60	66	16	17
JV	M	98.7	98.6	76	72	20	16
DZ	M	98.4	98.8	72	72	12	9
Range		97.7-100.5	97.7-100.5	60-81	62-81	12-20	9-17
Mean		99.0	99.1	71	71	16	14

NOTE: The oximeter saturations indicated in excess of 100 percent breathing oxygen at ground level appear to be due to a shift in baseline due to an increase of temperature of the pinna of the ear resulting in vasodilatation and increased perfusion. Earpiece had been worn approximately 1 hour.

TABLE 14. Summary of Measurements of the Carbon Dioxide Content of the Rebreathing Bag and Mask Facepiece as Determined at Ground Level Immediately Postflight

Subject	ating Minute 1 Max.	Min.	3 Max.	Min.	Exercising Minute 1 Max.	Min.	3 Max.	Min.	Reading Minute 1 Max.	Min.	3 Max.	Min.	Mask Sampling Location	Type Mask*
DR	5.00	0.50	3.20	0.50	8.90	3.20	8.90	3.00	--	--	--	--	bag	1
JH	--	--	--	--	2.20	0.75	3.00	1.00	0.50	0.50	0.50	0.50	bag	1
JT	1.00	0.50	2.00	0.70	2.50	1.00	3.00	1.00	3.00	0.50	2.00	0.20	bag	1
BH	4.10	0.50	4.00	0.50	4.80	0.70	4.80	0.70	4.50	0.70	4.50	0.70	facepiece	1
JV	3.70	0.50	4.00	1.00	4.50	0.60	4.40	0.40	5.00	0.40	4.20	0.60	facepiece	1
DZ	4.00	0.30	4.00	0.30	4.80	0.50	5.00	0.60	4.70	0.50	4.30	0.60	facepiece	1
DZ	4.20	0.50	3.80	0.30	4.80	0.40	5.00	0.50	4.50	0.70	4.40	0.80	facepiece	1
BH	3.00	1.00	3.50	1.00	4.00	1.00	4.00	1.50	1.00	0.50	1.00	0.50	bag	2
BH	5.00	0.20	6.00	0.20	6.00	0.50	6.50	1.50	6.00	1.00	6.00	1.00	facepiece	2
DZ	5.00	0.50	5.00	0.50	5.50	0.50	6.00	0.50	6.00	0.50	5.50	0.70	facepiece	3
DZ	3.50	1.00	2.00	0.70	2.00	1.00	1.00	1.00	3.00	1.50	2.80	1.00	lag	3

*1 - Cessna Mask
2 - Zep-Aro Mask (Cessna Part No. C 166009-0401)
3 - Ohio Chemical K-S Mask

TABLE 15. Summary of Subjective Evaluations of Speech Intelligibility While Reading at Various Altitudes

CESSNA MASK
(Voice transmitted through the mask)

Subject	Sex	20,000 ft Volume - Clarity	25,000 ft Volume - Clarity	30,000 ft Volume - Clarity	Ground Postflight Volume - Clarity
DR	M	5 x 4	5 x 4	5 x 4	
JT	M	4 x 4	5 x 5	5 x 4	5 x 5
JH	F	5 x 5	5 x 5	5 x 5	
MZ	F	5 x 5	5 x 5	5 x 4	
LZ	F	4 x 4	4 x 3	5 x 3	
DM	F	5 x 5	5 x 5	5 x 5	
GF	M	5 x 5	5 x 5	5 x 4	
BH	M	5 x 5	5 x 4	5 x 3	
JV	M	5 x 5	5 x 5	5 x 5	
DZ	M	5 x 5	5 x 5	5 x 5	
OHIO CHEMICAL K-S Mask (Voice transmitted through the mask)					
DZ	M	5 x 5	5 x 5	5 x 5	5 x 5
ZEP-ARO MASK (CESSNA PART NO. C 166009-0401) (Voice transmitted through mask-mounted microphone)					
BH	M	5 x 5	5 x 5	5 x 5	5 x 5

TABLE 16. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subject BH Wearing a Zep-Aro Constant-Flow Mask (Cessna Part No. C 166009-0401) With the Zep-Aro Orifice (F 365-1080-2) at an Oxygen Supply Pressure of 70 psi. Mask Equipped With a Microphone

Altitude (ft)	Condition	Oximeter Percent Minute 1	Oximeter Percent Minute 3	Heart Rate Minute 1	Heart Rate Minute 3	Respiratory Rate Minute 1	Respiratory Rate Minute 3
Ground	Preflight	97		68		11	
14,000	Resting	86.0	86.5	76	74	10	10
	Exercise	85.0	88.5	94	94	18	15
	DON MASK						
20,000	Exercise	97.4	97.8	72	76	12	12
	Reading	97.4	98.8	74	78	14	14
25,000	Exercise	98.0	97.0	74	76	13	14
	Reading	96.2	98.3	82	84	14	16
30,000	Exercise	91.5	86.0	--	--	12	12
	Reading	84.0	88.0	--	--	14	15
	POSTFLIGHT						
Ground	Resting	99.2	99.3	58	60	12	14
	Exercise	99.2	99.0	70	74	13	14
	Reading	99.2	99.3	68	68	12	8

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TABLE 17. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Zep-Aro Constant-Flow Mask (Cessna Part No. C 166009-0401) as Derived From Estimates of the End Expiratory Nitrogen. Subject BH. Zep-Aro Orifice (F 365-1080-2) at Pressure of 70 psi

Altitude (ft)	Condition	End Expiratory Nitrogen Minute 1	3	Dilution Percent Minute 1	3	Percent Oxygen from Supply Minute 1	3	Ambient Minute 1	3	Supply + Ambient Minute 1	3	Calculated $P_{T_{O_2}}$ mmHg Minute 1	3
20,000	Exercise	42	47	53	60	47	40	11	13	58	53	175	160
	Reading	45	40	57	51	43	49	12	11	55	60	166	182
25,000	Exercise	42	43	53	54	47	47	11	11	58	57	136	134
	Reading	40	41	51	52	49	48	11	11	60	59	141	138
30,000	Exercise	44	48	56	61	44	39	12	13	56	52	100	93
	Reading	46	43	58	54	42	46	12	11	54	57	97	102
	POSTFLIGHT												
Ground	Resting	53	50	67	63	33	37	14	13	47	50		
	Exercise	55	55	70	70	30	30	15	15	45	45		
	Reading	54	54	68	68	32	32	14	14	46	46		

TABLE 18. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subject DZ Wearing Ohio Chemical K-S Mask With the Zep-Aro Orifice (F 365-1080-2) at an Oxygen Supply Pressure of 70 psi

Altitude (ft)	Condition	Oximeter Percent Minute 1	3	Heart Rate Minute 1	3	Respiratory Rate Minute 1	3
Ground	Preflight	97		82		8	
14,000	Resting	93.0	92.5	92	92	10	13
	Exercise	87.0	86.0	110	110	21	20
	DON MASK						
20,000	Exercise	98.0	98.0	102	96	18	15
	Reading	99.3	99.5	92	94	14	17
25,000	Exercise	91.0	92.0	104	102	15	17
	Reading	99.4	99.3	96	94	17	18
30,000	Exercise	90.0	84.8	106	118	16	19
	Reading	97.6	98.0	100	98	19	18
	POSTFLIGHT						
Ground	Resting	98.7	99.0	78	82	12	10
	Exercise	98.8	98.0	88	90	10	17
	Reading	99.0	99.3	82	82	13	11

TABLE 19. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Ohio Chemical K-S Mask as Derived From Estimates of the End Expiratory Nitrogen. Subject DZ. Zep-Aro Orifice (F 365-1080-2) at Pressure of 70 psi

Altitude (ft)	Condition	End Expiratory Nitrogen Minute 1	3	Dilution Percent Minute 1	3	Percent Oxygen from Supply Minute 1	3	Ambient Minute 1	3	Supply + Ambient Minute 1	3	Calculated $P_{T_{O_2}}$ mmHg Minute 1	3
20,000	Exercise	48	52	61	66	39	34	13	14	52	48	157	145
	Reading	51	50	65	63	35	37	14	13	49	50	148	151
25,000	Exercise	51	47	65	60	35	40	14	13	49	53	115	125
	Reading	46	46	58	58	42	42	12	12	54	54	127	127
30,000	Exercise	43	45	54	57	46	43	11	12	57	55	102	98
	Reading	42	40	53	51	47	49	11	11	58	60	104	107
	POSTFLIGHT												
Ground	Resting	53	54	67	68	33	32	14	14	47	46		
	Exercise	63	62	80	78	20	22	17	16	37	38		
	Reading	56	55	71	70	29	30	15	15	44	45		

TABLE 20. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subject DD During Two 1-Hour Extended Chamber Flights at 25,000 ft. Subject Wearing Cessna Mask With Zep-Aro Orifice (F 365-1080-2). Alternate Periods of Exercise and Rest at 25,000 ft

Subject	DD
Height	68 in
Weight	135 lb
Age	35 yr

Oxygen Supply Pressure - 70 psi

Altitude (ft)	Condition	Oximeter Percent Minute			Heart Rate Minute			Respiratory Rate Minute			Minutes at 25,000 ft
Ground	Preflight		95.5			94			12		
		1		3	1		3	1		3	
14,000	Resting	88.0		87.0	114		124	7		6	
		1	3	6	1	3	6	1	3	6	
	Exercise	87.0	85.4	85.0	138	136	137	11	14	12	
DON MASK											
		1		3	1		3	1		3	
	Exercise	98.8		99.5	112		116	12		13	
25,000	Resting	99.4		99.6	102		102	14		15	1- 9
	Exercise	99.4		98.5	116		122	15		13	10-16
	Resting	99.0		99.2	102		100	11		12	17-25
	Exercise	99.0		97.4	114		120	16		13	26-31
	Resting	98.0		99.3	104		104	8		13	32-41
	Exercise	98.8		98.5	116		120	14		17	42-47
	Resting	99.0		99.8	102		104	12		11	48-57
	Exercise	99.0		99.0	116		114	15		14	58-59

Oxygen Supply Pressure - 60 psi

Altitude (ft)	Condition	Oximeter Percent Minute			Heart Rate Minute			Respiratory Rate Minute			Minutes at 25,000 ft
Ground	Preflight		94.5			90			17		
		1		3	1		3	1		3	
14,000	Resting	89.5		89.0	100		108	10		7	
		1	3	6	1	3	6	1	3	6	
	Exercise	87.5	-	88.0	94	-	134	6	-	7	
DON MASK											
		1		3	1		3	1		3	
	Exercise	97.0		99.0	98		94	7		6	
25,000	Resting	99.0		99.0	100		102	11		8	1- 9
	Exercise	98.0		96.3	112		116	10		12	10-16
	Resting	98.2		99.3	92		100	8		15	17-25
	Exercise	98.8		97.4	118		120	11		13	26-31
	Resting	98.6		99.6	112		110	13		10	32-41
	Exercise	99.0		98.1	114		116	14		17	42-47
	Resting	98.6		99.7	108		98	12		9	48-57
	Exercise	99.5		99.0	110		110	15		14	58-59

TABLE 21. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Cessna Mask During 1-Hour Extended Chamber Flight at 25,000 ft. Subject DD. Zep-Aro Orifice (F 365-1080-2). Data Derived From Estimate of the End Expiratory Nitrogen. Alternate Periods of Exercise and Rest at 25,000 ft

Altitude (ft)	Condition and Time at Altitude (Minute)	End Expiratory Nitrogen Minute 1	End Expiratory Nitrogen Minute 3	Dilution Percent Minute 1	Dilution Percent Minute 3	Percent Oxygen from Supply Minute 1	Percent Oxygen from Supply Minute 3	Percent Oxygen from Ambient Minute 1	Percent Oxygen from Ambient Minute 3	Percent Oxygen from Supply + Ambient Minute 1	Percent Oxygen from Supply + Ambient Minute 3	Calculated $P_{T_{O_2}}$ mmHg Minute 1	Calculated $P_{T_{O_2}}$ mmHg Minute 3
Oxygen Supply Pressure - 70 psi													
14,000	Exercise	50	52	63	66	37	34	13	14	50	48	200	192
25,000	Resting 1-9	20	21	25	27	75	73	5	6	80	79	188	186
	Exercise 10-16	35	40	44	51	56	49	9	11	65	60	153	141
	Resting 17-25	33	23	42	29	58	71	9	6	67	77	158	181
	Exercise 26-31	36	45	46	57	54	43	10	12	64	55	151	129
	Resting 32-41	33	23	42	29	58	71	9	6	67	77	158	181
	Exercise 42-47	33	37	42	47	58	53	9	10	67	63	158	148
	Resting 48-57	36	22	46	28	54	72	10	6	64	78	151	184
	Exercise 58-59	32	37	40	47	60	53	8	10	68	63	160	148
Oxygen Supply Pressure - 60 psi													
14,000	Exercise	53	51	67	65	33	35	14	14	47	49	188	196
25,000	Resting 1-9	28	25	35	32	65	68	7	7	72	75	169	177
	Exercise 10-16	35	42	44	53	56	47	9	11	65	58	153	136
	Resting 17-25	35	13	44	16	56	84	9	3	65	87	153	203
	Exercise 26-31	40	40	51	51	49	49	11	11	60	60	141	141
	Resting 32-41	28	23	35	29	65	71	7	6	72	77	169	181
	Exercise 42-47	36	39	45	49	55	51	9	10	64	61	151	144
	Resting 48-57	35	27	44	34	56	66	9	7	65	73	153	172
	Exercise 58-59	35	40	44	51	56	49	9	11	65	60	153	141

TABLE 22. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subject JV During 1-Hour Extended Chamber Flight at 30,000 ft. Subject Wearing Cessna Mask With Zep-Aro Orifice (F 365-1080-2). Alternate Periods of Exercise and Rest at 30,000 ft

Oxygen Supply Pressure - 70 psi

Altitude (ft)	Condition	Oximeter Percent Minute 1	Oximeter Percent Minute 3	Heart Rate Minute 1	Heart Rate Minute 3	Respiratory Rate Minute 1	Respiratory Rate Minute 3	Minutes at 30,000 ft
Ground	Preflight	94.5		84		17		
14,000	Resting	83.0	82.5	88	94	11	18	
	Exercise	76.0	77.0	108	114	22	22	
	DON MASK							
		1 Minute		1 Minute		1 Minute		
	Resting	98.0		80		11		
30,000	Resting	94.0	96.0	84	82	16	15	1- 9
	Exercise	90.0	83.0	102	108	22	25	10-16
	Resting	95.0	96.0	86	82	18	18	17-24
	Oxygen Supply Pressure Reduced From 70 to 60 psi							
	Resting	95.2	94.7	86	81	18	18	25-27
	Exercise	80.0	75.0	106	114	24	26	28-32

Remainder of Chamber Flight Aborted - Descent

TABLE 23. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Cessna Mask During 1-Hour Extended Chamber Flight at 30,000 ft. Subject JV. Zep-Aro Orifice (F 365-1080-2). Data Derived From Estimate of the End Expiratory Nitrogen. Alternate Periods of Exercise and Rest at 30,000 ft

Oxygen Supply Pressure - 70 psi

Altitude (ft)	Condition and Time at Altitude (Minute)	End Expiratory Nitrogen		Dilution Percent		Percent Oxygen from Supply		Percent Oxygen from Ambient		Percent Oxygen from Supply + Ambient		Calculated $P_{T_{O_2}}$ mmHg	
14,000	Resting	48		61		19		13		52		208	
30,000	Resting 1-9	3	20	4	25	96	75	0.8	5	97	80	174	143
	Exercise 10-16	38	40	48	51	52	49	10	11	62	60	111	107
	Resting 17-24	32	19	40	24	60	76	8	5	68	81	122	145
	Supply Pressure Reduced to 60 psi												
	Resting 25-27	28	28	35	35	65	65	7	7	72	72	124	129
	Exercise 28-32	47	48	60	61	40	39	13	13	53	52	95	93

TABLE 24. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subject DD Wearing the Cessna Mask During Chamber Flights to Simultaneously Measure Nitrogen in the Facepiece and Nares. Zep-Aro Orifice (F 365-1080-2) at an Oxygen Supply Pressure of 70 psi

Altitude (ft)	Condition	Oximeter Percent Minute		Heart Rate Minute		Respiratory Rate Minute	
Ground Level	Preflight	96		82		18	
		1	6	1	6	1	6
14,000	Rest, Baseline	94	78	86	92	9	9
	Exercise	80	74	112	108	8	7
	MASK DONNED						
		1	3	1	3	1	3
	Resting	85	93	86	76	10	6
		1	6	1	6	1	6
25,000	Resting	95	95	80	84	12	8
	Exercise	95	95	98	102	9	12
30,000	Resting	94	96	82	86	7	10
	Exercise	95	94	102	104	13	13

TABLE 25. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Cessna Mask at Chamber Flight Altitudes of 25,000 and 30,000 ft. Values Derived From Simultaneous Measurements of End Expiratory Nitrogen in the Mask Facepiece and the Nares. Subject DD. Zep-Aro Orifice (F 365-1080-2). Oxygen Supply Pressure - 70 psi

Altitude (ft) and Condition	Measurement Location	End Expiratory Nitrogen Minute		Dilution Percent Minute		Percent Oxygen from: Supply Minute		Ambient Minute		Supply + Ambient Minute		Calculated $P_{T_{O_2}}$ mmHg Minute	
		1	2	1	2	1	2	1	2	1	2	1	2
14,000	Nasal	40	38	51	48	49	52	11	10	60	62	240	248
Resting	Mask	38	40	48	51	52	49	10	11	62	60	248	240
		1	6	1	6	1	6	1	6	1	6	1	6
25,000	Nasal	27	25	34	32	66	68	7	7	73	75	172	177
Resting	Mask	28	25	35	32	65	68	7	7	72	75	169	177
25,000	Nasal	33	37	42	47	58	53	9	10	67	63	158	148
Exercise	Mask	35	37	44	47	56	53	9	10	65	63	153	148
30,000	Nasal	20	18	25	23	75	77	5	5	80	82	143	147
Resting	Mask	20	20	25	25	75	75	5	5	80	80	143	143
30,000	Nasal	25	35	32	44	68	56	7	9	75	65	134	116
Exercise	Mask	24	35	30	44	70	56	6	9	76	65	136	116

TABLE 26. Blood Oxygen Saturation, and Heart and Respiratory Rates of Subject BH Wearing the Cessna Mask During Chamber Flights to Simultaneously Measure Nitrogen in the Facepiece and Nares. Zep-Aro Orifice (F 365-1080-2) at an Oxygen Supply Pressure of 70 psi

Altitude (ft)	Condition	Oximeter Percent Minute		Heart Rate Minute		Respiratory Rate Minute	
Ground Level	Preflight	95		66		20	
		1	6	1	6	1	6
14,000	Rest, Baseline	86	77	78	82	18	11
	Exercise	78	72	98	98	17	17
	MASK DONNED						
		1	3	1	3	1	3
	Resting	98	99	78	66	10	18
		1	6	1	6	1	6
27,500	Resting	95	98	94	74	17	19
	Exercise	94	94	86	90	18	21
30,000	Resting	96	97	80	72	19	19
	Exercise	92	89	90	94	23	22

TABLE 27. Percentage of Ambient Air and Oxygen Content of Inspired Gas Using the Cessna Mask at Chamber Flight Altitudes of 27,500 and 30,000 ft. Values Derived From Simultaneous Measurements of End Expiratory Nitrogen in the Mask Facepiece and the Nares. Subject BH. Zep-Aro Orifice (F 365-1080-2). Oxygen Supply Pressure - 70 psi

Altitude (ft) and Condition	Measurement Location	End Expiratory Nitrogen Minute		Dilution Percent Minute		Percent Oxygen from Supply Minute		Percent Oxygen from Ambient Minute		Percent Oxygen from Supply + Ambient Minute		Calculated $P_{T_{O_2}}$ mmHg Minute	
		1	2	1	2	1	2	1	2	1	2	1	2
14,000 Resting	Nasal	45	43	57	54	43	46	12	11	55	57	220	228
	Mask	40	37	51	47	49	53	11	10	60	63	240	252
		1	6	1	6	1	6	1	6	1	6	1	6
27,500 Resting	Nasal	26	25	33	32	67	68	7	7	74	75	152	154
	Mask	24	24	30	30	70	70	6	6	76	76	157	157
27,500 Exercise	Nasal	40	40	51	51	49	49	11	11	60	60	124	124
	Mask	38	37	48	47	52	53	10	11	62	63	128	130
30,000 Resting	Nasal	25	23	32	29	68	71	7	6	75	77	134	138
	Mask	24	22	30	28	70	72	6	6	76	78	136	140
30,000 Reading	Nasal	33	--	42	--	58	--	9	-	67	--	120	---
	Mask	34	--	43	--	57	--	9	-	66	--	118	---
30,000 Exercise	Nasal	35	37	44	47	56	53	9	10	65	63	116	113
	Mask	33	33	42	42	58	58	9	9	67	67	120	120

PERFORMANCE CHARACTERISTICS OF PORTABLE FIRST AID CHEMICAL OXYGEN GENERATORS

D. deSteiguer, E. B. McFadden, and J. M. Simpson

I. Introduction.

Portable equipment for administration of first aid oxygen to airline passengers has been carried aboard air carrier aircraft for many years. Although these systems use high pressure gaseous oxygen, the past history of their deployment and use has been relatively free of accidents or serious incidents. However, several recent accidents involving these units stimulated interest in the airline industry in replacing them with chemical oxygen generators on a fleet-wide basis. In addition to safety considerations, reduced weight, ease of operation, maintenance simplicity, and cost factors make replacement with a chemical system attractive.

Essentially, chemical oxygen generators consist of a quantity of an alkali-metal chlorate enriched with a solid fuel such as iron to produce sufficient heat for decomposition of the chlorate and liberation of oxygen. Additional chemicals and filters are added or superimposed downstream in the generator to insure oxygen purity (1).

This investigation was limited to a study of the applicability in aviation of using readily available, off-the-shelf, portable first aid chemical oxygen generators marketed to the medical profession. Chemical oxygen generators for emergency passenger use in the event of decompression have been developed and qualified for aviation and are being used aboard the C5A, DC-10, and L-1011 aircraft. Chemical first aid oxygen systems evaluated in this study in no way replace emergency systems; they are meant to be used for first aid therapy only under normal conditions. Airlines report the use of first aid oxygen to be relatively frequent compared to the use of passenger emergency oxygen. To facilitate administration of first aid oxygen by the cabin crew, a first aid portable unit should be lightweight, reliable, and simple to operate, should produce therapeutic oxygen flows, and should not create a hazard in itself.

II. Method.

Two commercially available chemical oxygen generators designed for medical applications were evaluated for reliability, oxygen production, and physiological efficiency (ability to maintain an increased tracheal oxygen partial pressure in human subjects). The units tested were the Scott Med-Ox (Scott Aviation, Lancaster, New York) and the Life Support S.O.S. (Life Support, Melbourne, Florida) generator systems with respective canisters and masks.

This investigation covered:

A. A study of the physical properties of the generator systems. This phase was conducted in an altitude chamber with a pressure equivalent of 8,000 ft, the normal cabin pressure of inflight air carrier aircraft. This altitude provided for the maximum volume expansion of generated gases expected to be encountered with the intended use of these systems. Flow rates were measured with a National Instrument Laboratory wet flowmeter that had been calibrated to NBS standards. Ignitor reliability and total oxygen generation times were recorded. Gas temperatures were recorded with matched thermistors located between the generator and the mask outlet. A randomized design was used to select the particular generator and canister for each test.

B. A study of the physical properties of the generator systems and the physiological response from the use of these systems. As in the first phase, ignitor reliability, flow rates, and total oxygen generation times were recorded. Testing was conducted in an altitude chamber at a pressure equivalent of 8,000 ft and at 1,250 ft, or ground level at Oklahoma City. The test population were healthy, 18- to 28-yr-old male and female subjects, with a ratio of 4 males to 1 female, and within the male subjects, a ratio of clean shaven to bearded of 4 to 1. Immediately before the test sequence, each subject donned a crew-type oxygen mask that was coupled to a flowmeter and then exercised on a bicycle ergometer until a ventilation rate of 15 L/min was established through adjustment of the constant work mode. The subject then put on the appropriate test mask and began exercise at the previously established level while the selected canister(s) was activated. The test continued until such time that oxygen production by the generator ceased. Two small microcatheter tubes for gas sampling were positioned through the facepiece of the test mask in a manner not to compromise the mask performance or significantly alter its weight or facial fit. The output from these sample tubes was delivered directly to gaseous nitrogen analyzers for end expiratory nitrogen determinations. From the end expiratory nitrogen values, tracheal oxygen partial pressures were calculated on a breath-by-breath basis (2), adjusted to the equivalent of sea level or zero elevation; the means, standard deviations, and other appropriate tests were performed with computer techniques.

C. A study of the physiological efficiency of three types of oxygen masks in common use in the medical or aviation professions. The three types tested were: (i) an open-port, formed mask with a rebreather bag of the type commonly used in hospitals, (ii) a phase-dilution conical type with a feather edge used in the aviation industry, and (iii) a phase-dilution, modified conical type with inner facial seal and stacked valves used in the aviation industry. Each subject was tested with all three masks and, on

completion of the test, gave a personal assessment of the mask for fit, leakage, and comfort. The order of mask testing was randomized for each subject to control the influence of the first mask encounter on the evaluation procedures. Oxygen was precisely metered to each mask, first at 3 and then at 4 L/min, or the reverse, depending on the randomization process, while the subject exercised on a constant work ergometer for 4 min each in a sequence of 0, 120, and 400 kilogram meters/min. Tracheal oxygen partial pressures were determined continuously as in the second phase.

III. Results.

The Life Support generator systems (Fig. 1) measured 23 x 10 x 19 cm for a volume of 4,370 cm^3 and for a total weight of 2.2 kg. This weight included three unexpended canisters, hose, mask, and case. The canisters measured 116 x 56 mm in diameter and weighed 380 g each.

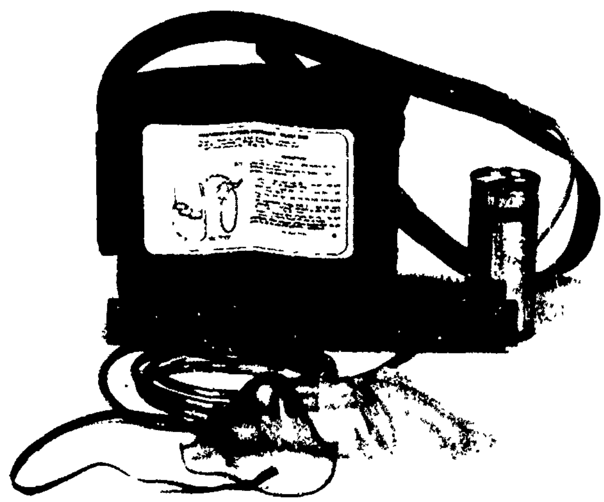

FIGURE 1. Life Support oxygen generator system.

Loading canisters into this unit simply requires insertion of the canister and closing the cover. This unit contains three actuator buttons of a recessed design, which reduces the potential for inadvertent actuation. This unit was provided with a "hospital type" mask of open-port design and a rebreather bag with the oxygen inlet between the mask cavity and the rebreather bag. The advertised

effective time for this product is 15 min of oxygen flow at 4 L/min per canister. The canisters can be actuated sequentially for 45 min of continuous flow at 4 L/min or simultaneously for increased flows of shorter duration. From a total of 30 canisters tested, 1 failed to actuate. This sample number is not sufficiently large to give a good reliability index. All canisters tested maintained oxygen generation for the full 15 min and with decreasing and variable flows to 17 min. Mean oxygen flow rates exceeded the advertised values and are presented in Tables 1 and 2.

TABLE 1. Average Flow (Liters/Minute, NTP) and Standard Deviation Within Canister(s) Across Time (0-15 Min)

Single Canister			Dual Canisters		
Test No.	$\overline{X}$ ±	S.D.	Test No.	$\overline{X}$ ±	S.D.
1	4.82	0.49	14	10.21	0.86
2	5.02	0.51	15	9.74	1.98
3	4.95	1.13	16	10.20	1.60
4	4.93	0.63	17	9.13	1.58
5	5.36	0.94	18	10.02	1.04
6	4.87	0.76	19	10.14	1.70
7	5.30	0.73	20	9.45	1.15
8	4.87	0.90	21	9.99	1.32
9	5.37	0.71			
10	5.30	0.66			
11	5.26	0.71			
12	5.15	0.69			
13	5.64	0.62			

TABLE 2. Average Flow (Liters/Minute, NTP) and Standard Deviation Across Canister(s) by Minutes (0-15 Min)

	Single Canister (N = 13)		Dual Canisters (N = 8)	
Min.	$\overline{X}$ ±	S.D.	$\overline{X}$ ±	S.D.
1	4.00	0.77	7.92	1.39
2	5.44	0.80	10.70	1.20
3	6.05	0.71	11.82	0.58
4	5.51	0.56	10.93	0.78
5	5.30	0.68	10.00	1.37
6	5.76	0.38	10.99	0.56
7	5.52	0.74	10.71	0.67
8	4.63	0.50	9.35	0.62
9	4.86	0.43	9.48	1.49
10	4.73	0.49	8.57	0.77
11	4.84	0.36	9.06	0.79
12	5.06	0.45	9.59	0.93
13	4.99	0.19	9.85	0.67
14	5.06	0.56	9.22	1.10
15	5.28	1.07	9.71	2.37

All flows are corrected to NTP. The small and variable amounts of moisture were disregarded. The values presented are for the first 15 min, the advertised time, with all data points included.

Tracheal oxygen partial pressure varied greatly between subjects and appeared to be highly influenced by respiratory rate and tidal volume as limited by a 15-L minute volume. These data are briefly generalized in Table 3.

TABLE 3. Tracheal Oxygen Partial Pressures Maintained in Human Subjects by S.O.S. Generator Units

	Mode of Operation	
	Single Canister	Dual Canister
Low Subject	180-190 mmpO_2	250-300 mmpO_2
High Subject	350-400 mmpO_2	400-430 mmpO_2

Note: All values are calculated from end expiratory nitrogen and are corrected to NTPD.

The generator system of the Scott Med-Ox unit (Fig. 2) measured 37 x 12 x 23 cm for a volume of 10,212 cm^3 and for a total weight of 3.4 kg. This weight included two unexpended canisters, hose, mask, and case. The canisters measured 248 x 64 mm in diameter and weighed 720 g each.

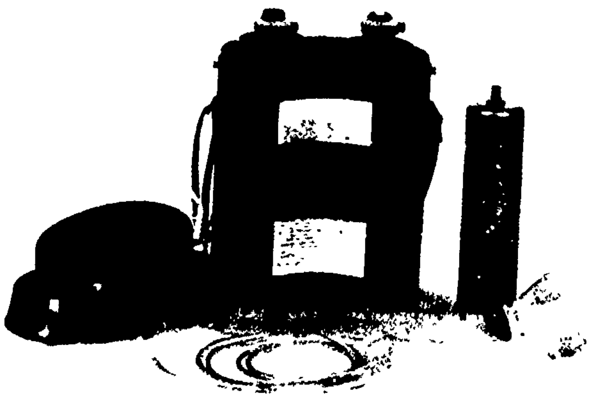

FIGURE 2. Scott oxygen generator system.

Loading this generator requires removing protective caps from the canister, inserting the canister, arming and locking the actuator assembly, and then screwing the actuator assembly set into position. This unit contains two actuator assemblies with locks that function as a deterrent to inadvertent activation. This unit was provided with an "aviation type" conical, feather edge, phase-dilution mask that incorporated a reservoir bag to which the oxygen flow is directed.

The advertised effective time is 25-30 min of oxygen flow at 3 L/min per canister. The canisters may be activated sequentially for 50-60 min of continuous flow at 3 L/min or simultaneously for increased flows of shorter duration. From a total of 31 canisters tested, 1 failed to activate. All canisters tested maintained oxygen generation for 27 min with decreasing and variable flows to 32 min. With two exceptions, oxygen flow rates exceeded the advertised values and are presented in Tables 4 and 5.

All flows are corrected to NTP. The small and variable amounts of moisture were disregarded. The values presented are for the first 27 min, with all data points included.

One canister was below the 3 L/min flow for several minutes and dropped as low as 1.48 L/min. One other canister dropped below the 3 L/min flow for about 2 min, with a low of 2.23 L/min.

TABLE 4. Average Flow (Liters/Minute, NTP) and Standard Deviation Within Canister(s) Across Time (0-27 Min)

Single Canister			Dual Canisters		
Test No.	$\bar{X}$ ±	S.D.	Test No.	$\bar{X}$ ±	S.D.
1	3.66	0.44	15	7.23	0.62
2	3.85	0.72	16	6.78	0.70
3	3.44	0.46	17	6.24	0.62
4	3.52	0.37	18	6.77	0.68
5	3.51	0.36	19	6.99	0.55
6	3.34	0.40	20	5.99	0.75
7	3.24	0.47	21	6.22	0.68
8	3.11	0.56	22	6.39	0.56
9	3.60	0.63			
10	3.66	0.44			
11	3.68	0.52			
12	3.60	0.50			
13	3.63	0.40			
14	3.56	0.39			

TABLE 5. Average Flow (Liters/Minute, NTP) and Standard Deviation Across Canister(s) by Minutes (0-27 Min)

	Single Canister (N = 14)		Dual Canisters (N = 8)	
Min.	$\bar{X}$ ±	S.D.	$\bar{X}$ ±	S.D.
1	3.90	0.74	7.37	0.46
2	3.84	0.51	7.25	0.54
3	3.71	0.50	6.38	0.75
4	3.95	0.68	6.37	0.79
5	3.60	0.90	6.59	0.79
6	3.62	0.80	6.83	0.97
7	3.77	0.91	6.67	1.14
8	3.70	0.51	6.95	0.92
9	3.89	0.42	7.02	1.12
10	3.75	0.53	6.50	1.22
11	3.70	0.53	6.63	1.29
12	3.37	0.48	6.61	0.63
13	3.20	0.67	6.30	0.63
14	3.39	0.29	6.25	0.61
15	3.29	0.34	5.97	0.70
16	3.33	0.21	6.03	0.51
17	3.29	0.22	6.28	0.47
18	3.36	0.27	6.43	0.26
19	3.28	0.23	6.37	0.36
20	3.24	0.27	6.39	0.40
21	3.32	0.28	6.51	0.35
22	3.42	0.19	6.40	0.17
23	3.41	0.16	6.37	0.42
24	3.44	0.23	6.84	0.40
25	3.54	0.16	6.66	0.52
26	3.51	0.26	6.85	0.48
27	3.59	0.45	6.80	1.02

Tracheal oxygen partial pressure varied greatly between subjects and appeared to be highly influenced by respiratory rate and tidal volume as limited by a 15-L minute volume. These data are briefly generalized in Table 6.

TABLE 6. Tracheal Oxygen Partial Pressures Maintained in Human Subjects by Scott Med-Ox Generator Units

	Mode of Operation	
	Single Canister	Dual Canister
Low Subject	200-250 $mmpO_2$	300-350 $mmpO_2$
High Subject	300-350 $mmpO_2$	450-520 $mmpO_2$

Note: All values are calculated from end expiratory nitrogen and are corrected to NTPD.

In both units the temperature of the oxygen produced during generation equilibrated with the environmental temperature well in advance to mask delivery. Tactile examination of the generator surfaces during operation did not identify any areas of excess temperatures which might produce contact burns. Precautions should be exercised when handling spent canisters until sufficient cooling has occurred.

Of the three types of masks tested in the third phase, the subjects identified the hospital-type mask as the mask most comfortable to wear; however, they indicated they felt the modified conical with inner face seal to be the best mask. Tracheal pO_2 values were higher with the modified conical mask for the flow rates tested. These data are presented in Table 7.

IV. Summary.

Two commercially available oxygen generators designed for the medical profession were tested for applicability to first aid use aboard pressurized aircraft. Except for brief deviations, both units produced oxygen above the advertised rate and beyond the advertised time. For medical uses, these deviations below the specified flow would appear to be inconsequential.

A comparison of the flow rates and tracheal pO_2 values maintained by the two generator units demonstrates the better efficiency obtained by using an aviation-type conical mask as compared to the open-port hospital-type mask, especially when low variable flows are involved. The Scott generator unit maintained a higher tracheal pO_2 with a lower oxygen flow rate than that maintained by the Life Support generator unit. This advantage is derived primarily from the reservoir bag and valves of the aviation-type mask provided with the Scott generator unit.

Three commercially available oxygen masks, an open-port hospital type, a phase-dilution conical aviation type, and a phase-dilution modified conical aviation type were compared at precisely controlled flows of 3 and 4 L of oxygen per minute. A higher tracheal pO_2 was maintained at these flow rates by the modified conical aviation mask when the subjects were resting quietly. As the exercise level of the subjects was increased, the performance of all the masks tended to converge and very little difference was detected.

At these very low flow rates, the valves of the conical aviation mask had a tendency to sequence in reverse order. This was not a significant problem with the modified conical aviation mask.

TABLE 7. Tracheal Oxygen Pressures in mmHg as Maintained by Three Types of Masks at Selected Flow Rates and Exercise Levels in Human Subjects

Exercise:	0 kg/min		120 kg/min		400 kg/min	
Flow, L/min:	3	4	3	4	3	4
Minute						
			Hospital Mask			
1	294 ± 36	349 ± 54	307 ± 46	351 ± 55	275 ± 30	314 ± 41
2	318 ± 43	384 ± 69	287 ± 40	340 ± 45	247 ± 24	288 ± 35
3	331 ± 46	384 ± 81	282 ± 36	331 ± 41	236 ± 20	268 ± 26
			Conical Mask			
1	300 ± 57	341 ± 54	288 ± 35	335 ± 49	254 ± 22	294 ± 33
2	329 ± 60	375 ± 55	272 ± 34	313 ± 41	235 ± 19	262 ± 21
3	338 ± 54	392 ± 62	268 ± 27	307 ± 40	228 ± 16	256 ± 17
			Modified Mask			
1	323 ± 44	359 ± 64	308 ± 40	359 ± 52	269 ± 25	314 ± 39
2	367 ± 48	416 ± 69	288 ± 31	341 ± 39	243 ± 17	276 ± 26
3	380 ± 54	440 ± 72	288 ± 28	336 ± 39	238 ± 14	266 ± 22

Note: All values are $mmpO_2$, mean ± standard deviation.

References

1. Harwood, V. N.: Chemical Oxygen Generator for Business and Utility Aircraft, Society of Automotive Engineers, New York, N. Y., March 1971.

2. McFadden, E. B.: Evaluation of the Physiological Protective Efficiency of a New Prototype Disposable Passenger Mask, FAA Office of Aviation Medicine Report No. AM-66-7, 1966.

PHYSIOLOGICAL EVALUATION OF THE PROTECTIVE CAPACITY OF THE PROTECTIVE MBU-8/P MILITARY PASSENGER OXYGEN MASK

E. B. McFadden, D. deSteiguer, and J. M. Simpson

I. Introduction.

The civil air carrier fleet's use of flight altitudes to 41,000 ft has been the primary impetus for the development of modern passenger oxygen systems. The systems are designed for automatic mask presentation in the event of decompression. They must provide an oxygen flow sufficient to maintain a mean tracheal oxygen partial pressure of not less than 83.8 mmHg at a tidal volume of 1,100 cc and a minute volume of 30 L/min BTPS up to and including 40,000 ft, as specified in the Federal Aviation Regulations, National Aerospace Standard (NAS) 1179, and FAA TSO-C64.

As a component of oxygen systems, U.S. air carriers use a continuous-flow reservoir mask of the phase-dilution type. A mask of this design meets the performance requirements for passenger use; does not require excessive oxygen flow rates; may be used with gaseous supplies or chemical generators; and is relatively simple in design though not in principle. The continuous-flow reservoir mask incorporates a flexible bag between the oxygen delivery tube and the mask inhalation valve. The continuous flow of oxygen accumulates in the reservoir bag during the exhalation portion of the respiratory cycle, thereby providing a drawdown capability during inhalation. During inspiration the mask wearer receives 100 percent oxygen until completion of the inhalation process or collapse of the reservoir bag. Once the reservoir bag has been emptied, a sensitive dilution valve is activated to provide the necessary volume of ambient air for completion of the inspiratory process. In this manner, 100 percent oxygen is provided at the most advantageous time (i.e., the first part of the inspiratory cycle) and oxygen diluted with ambient air is provided during the latter portion of the inhalation, filling the upper portion of the respiratory tract where gas exchange is nil. Furthermore, the air-diluted oxygen is exhaled first and consequently washed from the system prior to the next inhalation.

Performance is reduced by inboard mask leakage due to poor facial fit, a respiratory minute volume that is considerably greater than the flow of oxygen to the mask, and improperly sequenced valving. Reduced performance becomes critical as the decompression approaches 40,000 ft. However, at altitudes of less than 40,000 ft, the dilution of supplied oxygen with ambient air through the dilution valve is utilized as a means of conserving a finite aircraft oxygen supply while simultaneously providing the necessary mean tracheal oxygen partial pressure for the passengers. With proper facial fit, modern masks of this type are capable of providing the necessary protection in the event of decompression

to 40,000 ft. A more detailed discussion of this and other types of passenger oxygen masks is presented by McFadden (3).

With the concurrent increase in flight altitudes and the rapid expansion of air transportation following World War II, considerable attention was directed to the development of safety standards for passengers and crew in the event of a failure of cabin pressurization. The development of the K-S disposable mask by United Air Lines personnel and the subsequent physiological testing by the University of Illinois and the USAF School of Aerospace Medicine are reported by Tuttle et al. (4), Luft (5), and also by McFadden et al. (6) of the FAA.

Tuttle et al. (4) describe the mask as the rebreather dilution type with constant flow of oxygen and consisting of a double bag of light, transparent plastic material. The inner bag fits well over the oronasal region and communicates through two holes with the outer rebreather bag into which oxygen is supplied. Two smaller holes in the inner bag give direct access to ambient air. An adjustable elastic strap secures the mask around the head and a soft metal strap inserted into the upper rim of the facepiece can be molded readily to the nose and cheeks of the individual.

Physiological testing with the K-S mask demonstrated that satisfactory arterial oxygen saturation could be established and maintained following decomressions from 6,000 to 25,000 ft when an oxygen flow of 3 L/min STPD was provided to the mask. The use of this mask was not recommended for decompressions above 25,000 ft. Shortly thereafter the K-S mask was adopted by the military for use in flights carrying troups and dependents. In the ensuing years jet transport aircraft that utilized flight profiles to 41,000 ft were introduced. These flight altitudes far exceeded the performance capacity of this mask to provide protection in the event of a serious decompression. Consequently, the procurement of a replacement mask that would provide protective capabilities to 40,000 ft was initiated. This is a report of the physiological testing for the military of the prototype MBU-8/P mask to FAA and National Aerospace Standards applicable to civil air carrier jet transport aircraft.

II. Method.

Ten (five civilian and five Air Force personnel, all having been chamber qualified to 40,000 ft), young-to-middle-aged, healthy, male subjects were used during the physiological performance portion of the mask evaluation. Ten experienced chamber safety observers were provided from Air Force and FAA personnel.

Five prototype Air Force MBU-8/P continuous-flow reservoir-type passenger oxygen masks (Sierra Engineering Co., Sierra Madre, Calif.) were used during the testing sequence.

Two small microcatheter tubes (PE 60) for gas sampling were positioned through the facepiece of the mask in a manner that would not compromise the mask performance or alter its weight or facial fit to any significant degree. The output from one sample tube was delivered directly to a gaseous nitrogen analyzer (Custom Engineering and Development Co., Model 300 AR Nitralyzer) for end expiratory nitrogen determinations. The output from the second sample tube was passed through a small reservoir-integrator to a second nitrogen analyzer for the determination of mean mask nitrogen. A sample rate of 3 cc per minute for each was established by maintaining an absolute pressure of 0.6 mmHg at the analyzer detectors.

A constant-torque bicycle ergometer was positioned in the altitude chamber for operation from an auxiliary chair. Regulated exercise was used to establish the desired respiratory minute volume in preference to the practice of hyperventilation.

The flow of oxygen to the mask was regulated by an altitude-sensitive regulator of the type used in the passenger oxygen systems of jet transport aircraft. The output from this regulator was routed outside the chamber, passed through the output orifice, then through a flowmeter and needle-valve arrangement to obtain precise measurement and control, and was then passed back into the chamber to the test mask. Oxygen flow was limited to the minimum rate as provided by the outlet assembly (P/N 110112-01) used in the C-141 aircraft (Figs. 1 and 2).

Immediately before ascent the test subject was instrumented for EKG monitoring with three-position chest electrodes and for blood oxygen saturation with a Waters Model 350 Oximeter attached to the pinna of the right ear.

Visual recording of the subjects during the flight profile was accomplished with cinematographic techniques. Cameras were positioned for observation of the subject's face and of the reservoir bag of the test mask.

Following a test of the subject's ability to equalize ear pressures, the chamber was decompressed to 14,000 ft. The subject rested quietly until blood oxygen saturation stabilized and baselines were recorded. A brief period of controlled exercise on the bicycle ergometer followed to verify the measured response of blood oxygen saturation to hypoxia. The subject then donned a crew-type demand oxygen mask that provided 100 percent oxygen and returned to exercising on the bicycle ergometer. The exercise level was slowly adjusted until a respiratory minute volume of 25 to 30 L/min was achieved. After establishing the desired minute volume, exercise was discontinued and the subject changed from the crew mask to the MBU-8/P passenger mask. The test

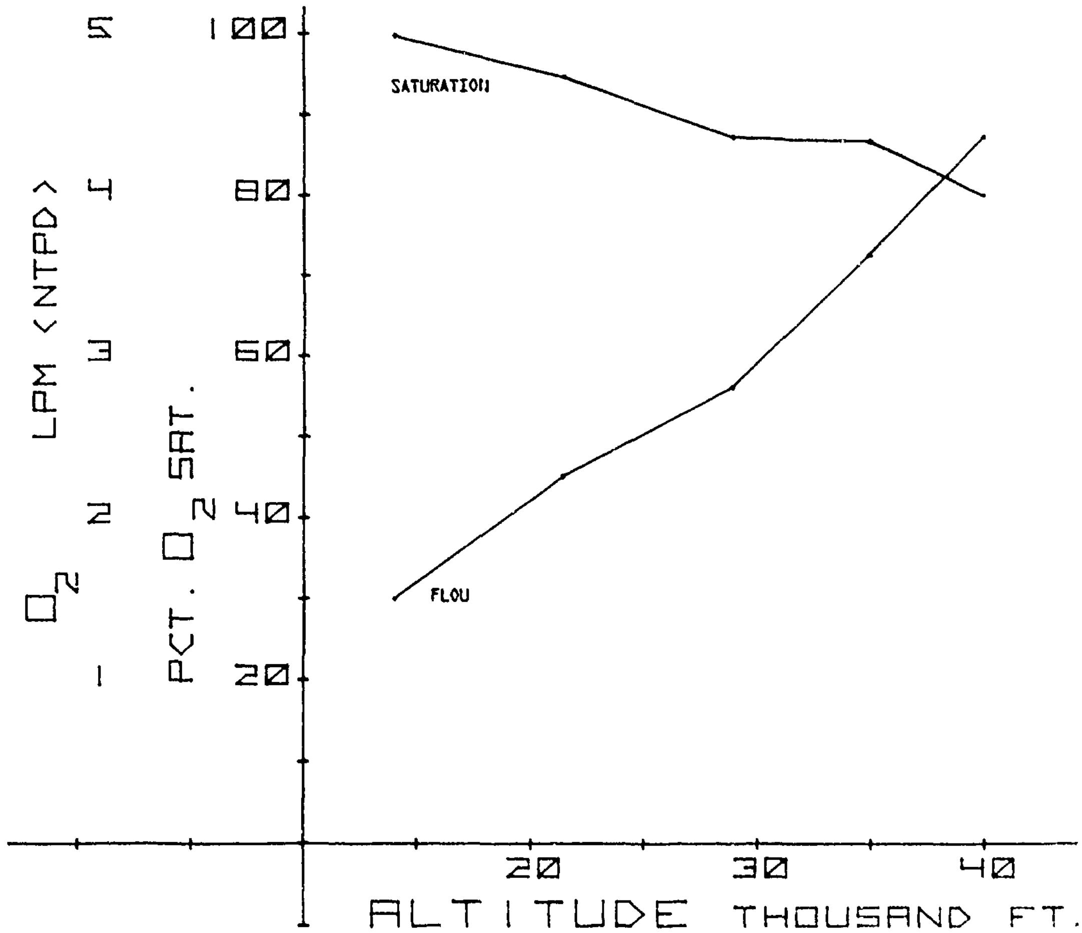

FIGURE 1. Blood oxygen saturation following 3 min of exercise at the indicated minimum oxygen flow rates.

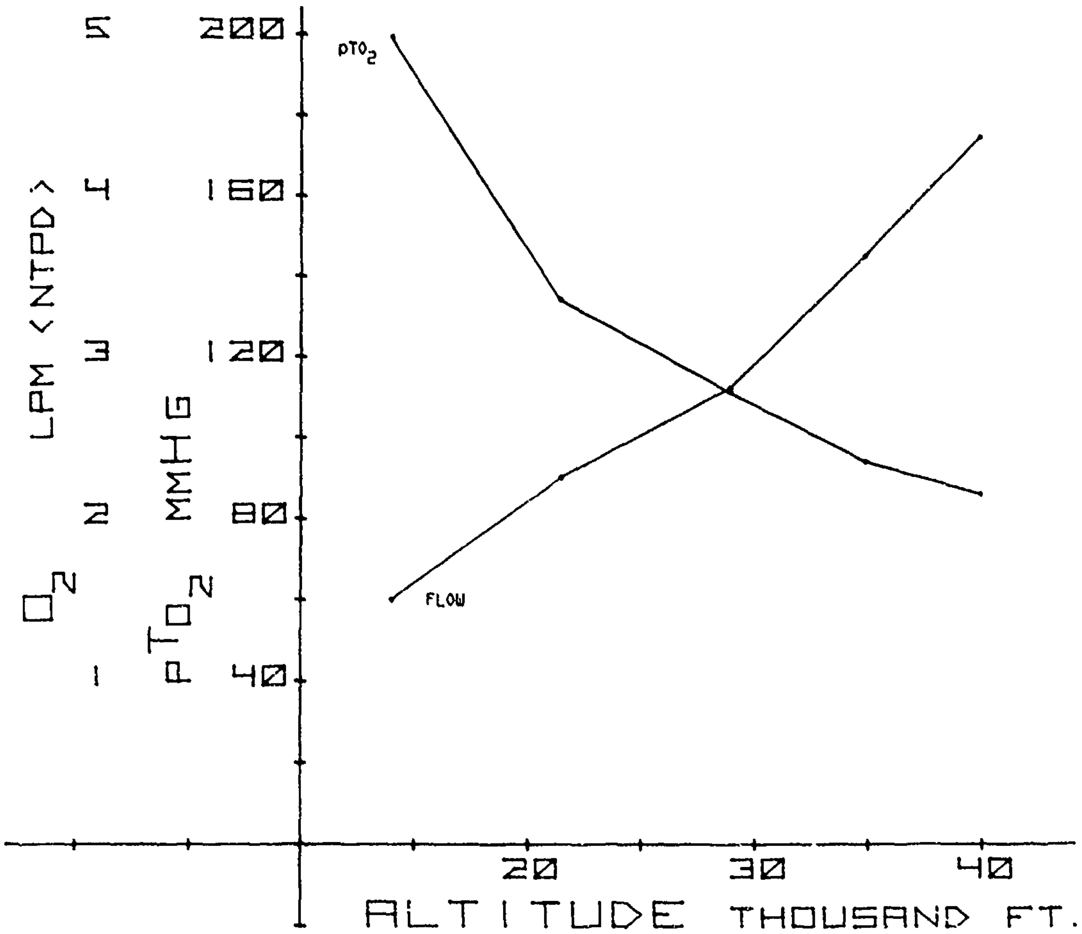

FIGURE 2. Tracheal oxygen partial pressure following 3 min of exercise at the indicated minimum oxygen flow rates.

sequence consisted of (i) the adjustment of the chamber pressure to the desired altitude, (ii) a brief rest period for the subject while instruments and flow rates were adjusted and stabilized, and (iii) 3 min of exercise by the subject. The test sequence was repeated at 14,000, 21,500, 29,000, 35,000, and 40,000 ft.

III. Results.

National Aerospace Standards recognize respiratory gas analyses and blood oxygen saturation determinations as the two methods to be used in altitude chamber tests of passenger oxygen masks. Both these methods were used simultaneously for monitoring the physiological performance of the MBU-8/P mask.

Blood oxygen saturation was measured directly with a Waters 350 ear oximeter. Blood oxygen saturation with corresponding oxygen flow rates following 3 min of exercise is presented in Figure 1. The determination of blood oxygen saturation with ear oximetry techniques provides a quick, real-time assessment of the degree of hypoxia an individual might be experiencing; however, there is frequently considerable variation in the results obtained and the technique is perhaps best used as a quick monitor or safety device. Alternately, more accurate analyses can be obtained from gaseous techniques; however, these data require considerable processing and are more difficult to utilize for quick physiological assessments.

Tracheal oxygen partial pressure is calculated from the end expiratory nitrogen as follows:

$$P_{T_{O_2}} = (B-47)\ (1-F_{IN_2})$$

Where: $P_{T_{O_2}}$ = tracheal oxygen partial pressure

B = ambient barometric pressure

47 = vapor pressure of water at body temperature and at 100 percent saturation

1 = unity

F_{IN_2} = fraction end expiratory nitrogen

These data, derived from the third minute at each specified altitude, with the corresponding oxygen flow rates, are presented in Figure 2. Correlation of these data is in close agreement with comparable values presented in the literature. Values for heart and respiration after 3 min of exercise are presented in Figure 3.

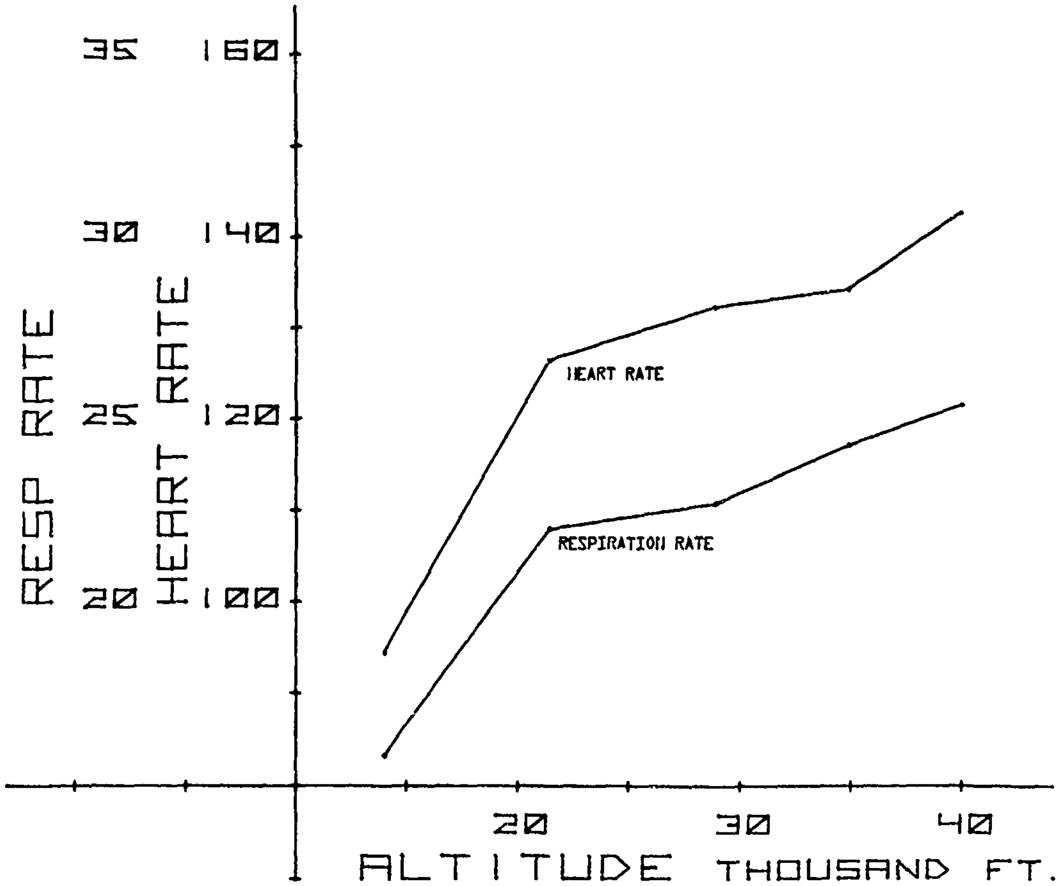

FIGURE 3. Heart and respiration rates following 3 min of standardized exercise at the indicated altitudes with the minimum oxygen flow provided as in Figures 1 and 2.

IV. Discussion.

The National Aerospace Standard 1179 and the FAA TSO-C64 provide precise guidelines for the physiological performance testing of passenger oxygen masks to be used in air carrier aircraft. These performance specifications require that a mean tracheal oxygen partial pressure of 83.8 mmHg or greater be maintained for the maximum altitude for which approval is desired. These guidelines further require that a respiratory minute volume of approximately 30 L/min BTPS be achieved by at least three subjects at an altitude within 5,000 ft of the maximum for which approval is desired. Induced hyperventilation may be used to achieve this minute volume. However, the use of hyperventilation has a tendency to overrate the physiological efficiency of a mask due to the decreased pCO_2 and resultant increased pO_2 that occur after the first few breaths. For a more detailed discussion of the effects of hyperventilation, see Comroe (7). The use of regulated exercise has a tendency to underestimate the physiological efficiency of a mask due to the increased oxygen consumption, particularly when compared with testing procedures that utilize sedated subjects. However, the identification of the proper workload to maintain the desired respiratory minute volume for an individual is difficult, especially when the degree of apprehension is often unpredictable.

In this study a workload was established for each subject that would produce a respiratory minute volume of approximately 30 L/min BTPS, this determination being accomplished at 14,000 ft where the effects of apprehension were minimal. The flow of oxygen to the test mask was precisely regulated to 4.35 L/min NTPD, or 37 L/min BTPS, at the 40,000-ft level. If the effects of anxiety are added to the ventilation rate produced by work, a minute volume of 37 L/min would be approached or even exceeded. In either case, if a rapid irregular respiration is encountered, the reservoir bag could be emptied and ambient air would then be drawn through the dilution valve. If the tidal volume were sufficiently great, a lowered pTO_2 could occur, causing an even higher ventilation rate and an ensuing rapid development of acute hypoxia. An examination of the tracheal oxygen partial pressure and blood oxygen saturation data for the 40,000-ft altitude demonstrates the results of having obtained a respiratory minute volume higher than expected; i.e., in excess of 30 L/min BTPS.

Testing was terminated during the third minute of exposure to 40,000 ft for subject 7, due to the development of acute hypoxia.

The quantification of impedance pneumograph data is difficult and, at times, highly questionable; however, it can readily be used as an indication of ventilation rate. A comparison of impedance pneumograph recordings obtained at 14,000 ft with a workload

regulated to give a minute volume of 25 to 30 L/min BTPS to the corresponding recordings from 40,000 ft indicates that the ventilation rate of subject 7 could have exceeded the 30 L/min desired by almost 50 percent while at the higher altitude. That the reservoir bag was being emptied during inspiration, with the resultant activation of the dilution valve, is confirmed through close examination of the motion picture film of this test.

To a lesser degree, the same problem was encountered in controlling the respiratory rates of subjects 4 and 6. These subjects did not exceed the minute volume to the extent that subject 7 did; however, analyses of the data and motion picture film indicated that activation of the dilution valve did occur. With the exception of subject 7 (with a pT_{O_2} of 83 mmHg), all subjects had a pT_{O_2} greater than 83.8 while resting at 40,000 ft.

V. Conclusions.

A. The prototype MBU-8/P passenger mask demonstrated an adequate capability to maintain human subjects in an acceptable physiological condition for limited exposures to 40,000-ft altitudes.

B. The use of controlled exercise to achieve a specified respiratory minute volume is the method of choice as opposed to hyperventilation. However, allowances should be made for the effects of apprehension if excessive respiratory rates are to be avoided. The effects of apprehension are most pronounced from 30,000 to 40,000 ft, the most crucial portion of a mask evaluation.

C. Analyses of physiological data and motion picture film indicate that the desired respiratory minute volume was exceeded by 3 of the 10 subjects while exercising at the 40,000-ft level. As this portion of the test was beyond the requirements of NAS-1179 and FAA TSO-C64, the test was not repeated.

D. If workloads and respiratory minute volumes in excess of those obtained in this study are anticipated, oxygen flow to the mask should be increased to compensate for increases in activity.

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HUMAN FACTORS REPORT OF THE INVESTIGATION OF THE IN-FLIGHT DECOMPRESSION, NOVEMBER 3, 1973, OF NATIONAL AIRLINES FLIGHT 27 (N60NA): A DC-10 EN ROUTE FROM HOUSTON INTERNATIONAL AIRPORT TO SAN FRANCISCO WITH 127 PERSONS ABOARD

D. deSteiguer

I. Introduction.

James M. Simpson and Don deSteiguer, FAA Civil Aeromedical Institute, were directed on November 5, 1973, to proceed to Albuquerque, New Mexico. They arrived on the afternoon of November 5, reported to the FAA Coordinator, and were assigned to the Human Factors Group by the National Transportation Safety Board Investigator-In-Charge. On November 5, 6, and 7, they participated in examination of the aircraft interior, decompression events, and equipment function and use. From November 8 through November 27, an intensive study was conducted to define the decompression and other events that occurred. DC-10 maintenance manuals from the FAA Aeronautical Center were examined in detail. The American Airlines Maintenance Facility, Tulsa, Oklahoma, made its maintenance and parts library available to these investigators.

II. Decompression.

The major penetrations into the aircraft fuselage were: (i) a cabin window at seat location 17H, area 160 in^2; (ii) into the center accessory compartment, area 160 in^2; and (iii) two into the forward cargo and belly compartments--a forward penetration, area 230 in^2, and an aft penetration, area 140 in^2. There were numerous small penetrations.

A rapid and severe decompression occurred in the forward cargo compartment. This decompression was caused by large penetrations directly into a compartment having a small volume.

A rapid and severe decompression occurred in the lower galley. There were no direct penetrations into this compartment. The major source of decompression was through the perimeters of the two cargo doors between the forward cargo compartment and the lower galley. The openings around these doors were 1/8 in by one-half to two-thirds of the door perimeter of 220 in. Statements by the two flight attendants stationed in this compartment are in accordance with a rapid and severe decompression. The observed incidents were: (i) a rapid reduction in air temperature; (ii) the opening of doors from modular units and lifts; (iii) the flow of paper articles in an aft direction; (iv) the drop of the personnel lift; and (v) the loss of consciousness by the two attendants.

A slower and less severe decompression occurred in the passenger cabin and flight compartment. The loss of the cabin window at seat 17H was directly responsible for the passenger in that seat being ejected from the aircraft. The area of penetration associated with the cabin window was temporarily and partly blocked with the body of the ejected passenger. This passenger--a male, 5 ft 11 in, 160 lb-- had his seatbelt fastened loosely. The window was slightly to the rear of the passenger, and the wind blast exerted a force that caused the body to straighten and slip under the belt (as opposed to a forward force that would have doubled the body over the seatbelt). The actions of another male passenger in attempting to hold the ejected passenger by the legs and/or feet while he was partly out the window verify the temporary and partial obstruction of the area of window penetration. The time from window penetration to complete passenger ejection is not known. Four additional windows located from seats 16H through 19H received damage but were not penetrated.

Because of the large areas of connecting ports, the penetration into the center accessory compartment should be considered as a direct penetration into the passenger cabin.

Warning lights and signs that are coupled to a 10,000-ft pressure switch were on. A cabin altitude rate indicator reading of 5,000 ft/min was reported by the flight engineer; however, maximum cabin altitude was not determined. Oxygen masks in the passenger cabin were not automatically deployed. This indicates that either the passenger cabin did not reach the 14,000-ft equivalent altitude or the controlling electrical system, the No. 3 DC-bus, was nonfunctional. Preliminary information indicates the No. 3 DC-bus was inoperative. The cabin altitude warning horn did not sound. This device is also powered by the No. 3 DC-bus.

Statements by the flight attendants and pilot are in accordance with a mild decompression in the passenger cabin. One female passenger is reported to have lost consciousness in a forward lavatory. As this is the only reported case of loss of consciousness in the passenger cabin, one must consider the possibility of a lower pressure in the lavatory, related to the lavatory ventilation and exhaust system, as compared to the main cabin pressure. A second possibility is individual variation in susceptibility to hypoxia. A third possibility is physiological problems completely unrelated to the decompression or additive to the effects of the decompression. The exact cause of this passenger's loss of consciousness cannot be established from available information. The lack of loss of consciousness (in consideration of the number of persons involved), even when several people performed considerable physical activity without supplemental oxygen, support a mild decompression.

The quick initiation of the emergency descent, 6,000 ft/min, by the pilot helped control the severity of the decompression in the passenger cabin. The multitude of actions taken by the flight engineer for damage control and to conserve pressure are not available.

Two separate decompressions of the aircraft are identified, a rapid and severe decompression in the lower compartments and a slower and less severe loss of pressure in the passenger cabin. Two separate decompressions of different profiles establish a pressure differential between the upper and lower compartment systems. The presence of such a pressure differential is confirmed by the implosion of the upper deck door to the personnel lift and the forced opening of the lower deck lift doors. Structural damage to the upper portion of the lower deck personnel lift door confirms a pressure differential from the lift shaft to the lower galley.

The upper deck cart lift door is approximately one-half the area of the personnel door and is the stronger of the two. Because the lift shafts are connected, the pressure differential across the smaller door was relieved by the failure of the larger personnel door. At the time of decompression, the cart lift was in position in the lower galley and the personnel lift was reported to be in position in the upper deck. During decompression, the personnel lift was reported to have been forced to the down, or lower galley, position. The capacity of this lift is rated at 250 lb and, with a surface area of approximately 20 x 37 in or 740 in^2, a pressure differential of only 1/3 psi would load the lift to rated capacity. The forces required to override the drive mechanism and magnetic brakes are not available at this time. While investigators were on site, physical attempts to raise the personnel lift were not successful. It is reported that once electrical power was restored to the aircraft, the lift was operable. No visible signs of failure in the drive mechanism were detected.

If functioning properly, the lower galley drain plunger located in the bottom of the lift shaft would have no effect on the decompression or events related to the lift. The possibility of connecting openings between the belly compartment and the mechanism housing located in the lower lift shaft was discounted following examination of maintenance manuals. This should be confirmed on the aircraft.

III. Oxygen Systems.

The crew oxygen system consisted of Sierra quick-donning masks, Model No. 358 (Sierra Engineering Company, Sierra Madre, California), with Robertshaw mask-mounted regulators (Robertshaw

Controls Company, Anaheim, California) coupled to a gas supply. The crew oxygen system appeared to function correctly. Poor communication through the mask microphones was reported. This may have been due to high background noise, low amplifier adjustments, or system malfunction. As power was not available to the aircraft during our inspection, the reason was not determined.

The cabin oxygen system consisted of Sierra continuous-flow, phase-dilution conical masks (PN 289-601-5) coupled to Scott (Scott Aviation, Lancaster, New York) sodium chlorate oxygen generators (PN-801382-02 and 03). The entire unit is mounted in specified seat backs; additional units are located in lavatories, attendant stations, partitions, and the lower galley. Mask presentations should be automatic at 14,000 ft, this being controlled by an aneroid switch powered by the No. 3 DC-bus. Canister activation is manual, being accomplished by pulling on any of the masks attached to the unit. Lanyards connect the masks to the firing mechanism, a spring-activated striker pin. Upon activation, the primary chemical reaction in the generator core is the thermal decomposition of sodium chlorate (1,2).

$$2\ NaClO_3 + HEAT \rightarrow 2\ NaCl + 3O_2.$$

Sodium chlorate, when heated to 478°C, decomposes and yields approximately 45 percent of its weight as gaseous oxygen. The source of heat for this reaction is obtained from the reaction:

$$2\ Fe + O_2 \rightarrow 2FeO + HEAT$$

Because of the high core or reaction temperature, the canister is internally lined with an insulation layer. The surface temperature of the canister must not exceed 547°F when measured at an ambient temperature of 75°F ± 5°F (3). To prevent direct contact of persons, hoses, and masks with the generator, the designer has positioned a heat shield around the exposed portion of the canister. The heat shield is attached along the bottom; however, it is designed to spring out at the top and provide an air space between the canister and the shield. Heat shields are not required in those units mounted in overhead locations, such as lavatories, and in attendant seat installations.

Malfunctions that occurred in the cabin oxygen system include the following:

A. Mask presentation from the overhead unit located in the lower galley, a two-mask unit above and slightly to the side of the attendant seats, is slaved to the aneroid switch in the upper cabin. As a result, the oxygen masks were not presented to the two attendants, who were undergoing rapid and severe decompression, until after they had lost consciousness.

B. Electrical system failure prevented automatic presentation of all oxygen units to the passenger cabin. The No. 3 DC-bus, which provides power to close the switches in the passenger oxygen release system, was inoperative.

C. The backup system for mask presentation was manually deployed by the flight engineer. It is not known if this was due to calls from the lead attendant or was a routine operational procedure. Those oxygen systems controlled by the No. 3 AC-bus were not presented. It is reported that the No. 3 AC-bus was inoperative. A comparison of the seating chart to mask presentations indicates that approximately 24 passengers were initially without supplemental oxygen. A number of these passengers eventually moved to other seats. In five cases, passengers, and in one case, an attendant succeeded in forcing open the seat backs to gain access to the units.

D. The seat backs that contain oxygen systems are so designed to prevent passengers from opening the systems manually. Lifevests are located in seat back compartments adjacent to the oxygen units. These seat backs are designed to be opened manually by passengers in the event of a ditching. It is estimated that 25 percent of the lifevest compartments had been opened and, in most cases, the lifevests removed while passengers were looking for oxygen masks. This caused considerable confusion and delay on the part of a number of passengers in obtaining supplemental oxygen. A number of passengers were also confused as to where the oxygen masks would be presented; i.e., overhead drop vs. seat back systems.

E. At eight locations, when the masks were removed from the retaining brackets and pulled to activate the canisters, the activation lanyards entangled in the retaining brackets, making the mask unusable.

F. At one location, the oxygen reservoir bag was separated from the mask facepiece. This type of mask has a lanyard from the facepiece that passes through the reservoir bag to the oxygen inlet tube that provides strength to the assembly. When this type of mask is presented from overhead, a person is instructed to grab the mask and pull, the force being absorbed and transmitted by the lanyard. When this type of mask is presented in a seat back, it is possible for the user to grab the mask and bag, or only the bag, resulting in a separation of the reservoir bag from the facepiece.

G. At several locations, plastic mask components came in contact with the canisters, causing burns that left the mask useless.

H. At three locations, canisters were removed from seat backs and dropped into seats. The reasons for these actions are

unknown. This caused a fire in one seat, location 7D, that was extinguished with canned soft drink. The canister was transferred to the galley sink by an attendant. In the other two locations, seats and seatbelts were scorched. The attendants were not aware that heat was involved in the proper operation of oxygen generators.

I. In preparation for the emergency landing, the passengers were instructed to assume a position with head down and arms extended over the head and with hands to the seat back in front of them. The presence of the hot canisters in the seat backs caused considerable confusion.

J. Oxygen installations in the attendant seats are located in a compartment that is slightly raised above the floor. There is a large circular opening in the bottom of this container that allows considerable quantities of dirt and trash to collect in and around the mask and canister.

K. Portable oxygen units were covered with plastic bags. K-S disposable face masks were sealed in plastic bags and stored with or near the portable unit. The mask was not connected to the gas supply. In the lower galley, one portable unit had a smoke mask attached but was covered with a heavy plastic bag. One attendant managed to tear the bag partly open before losing consciousness. The K-S disposable mask is not sufficient for altitudes above 25,000 feet (4,5).

L. The presence of smoke and fumes in the passenger cabin is believed to have been due to the presence of Skydrol-500-B vapors from the hydraulic system.

IV. Evacuation.

Military firefighting units were alerted and in position along the runway before the aircraft landed. A normal landing was accomplished on runway 26. Foam was dispensed by the firefighting units to control possible fires associated with leaking fuel around the No. 3 powerplant.

Final aircraft position was 210° and a 17-knot wind at 270° was in effect during the evacuation. All exits were manned by attendants except the overwing exits 3L and 3R, which were manned by one attendant because of the general incapacitation of one attendant from the lower galley. All exits were opened for evacuation. The slide at 1L did not deploy automatically and the attendant attempted manual deployment. The slide did not inflate and this exit was not used for the evacuation. The slide at 1R did not deploy automatically and was deployed manually. All other slides deployed automatically; however, the wind blew the lower portion of 3R back upon the wing. The passengers attempting to evacuate at 3R were directed to 3L.

One invalid male was evacuated through 3L. The efforts of one attendant and one able-bodied man were required.

The attendants estimated the evacuation time to be 30 s, while the firefighters estimated closer to 60 s.

No serious injuries were reported. Ten persons complained of and were treated for ear pains. Ten other persons complained of smoke or fume inhalation. One person sustained a burned finger from a canister, one sustained an abrasion from a slide, and one reported a back sprain from the evacuation.

V. Discussion.

The decompression schematic (Figure 1) outlines the major airflows associated with the loss of pressure that occurred following fuselage penetration by No. 3 powerplant components. The schematic does not present any input from the No. 1 or No. 2 compressors, nor does it present the magnitude of flow in any direction. The lack of available data necessary for precise computations limits this analysis to rough estimates at best. However, these estimates should be useful in explaining the sequence of events that occurred, particularly in the lower galley.

Statements from the two flight attendants stationed in the lower galley indicate a rapid decompression by: (i) a rapid reduction in air temperature; (ii) the opening of doors from modular components; (iii) the flow of paper articles in the aft direction; (iv) the drop of the personnel lift; and (v) the loss of consciousness by the two attendants. Direct penetrations into the galley were not detected.

The time of consciousness during a rapid decompression while breathing air can be estimated. In a decompression from 10,000 to 30,000 ft, a consciousness time of 40-60 s can be predicted (Figure 2) (6).

The decompression profile may be roughly estimated for the various aircraft compartments if certain assumptions are acceptable in lieu of precise data. These assumptions include: (i) zero inflow of air into the compartment during the decompression; (ii) disregarding airflow across the penetration area; (iii) zero impediment to airflow within the compartment; (iv) no corrections for the multitude of time changes in gas temperatures, etc.; (v) no corrections for the pattern of airflow through the penetration; and (vi) maintenance of critical flow.

The equation for rapid decompression as presented by Haber and Clamann (7) is sufficient in view of the assumptions.

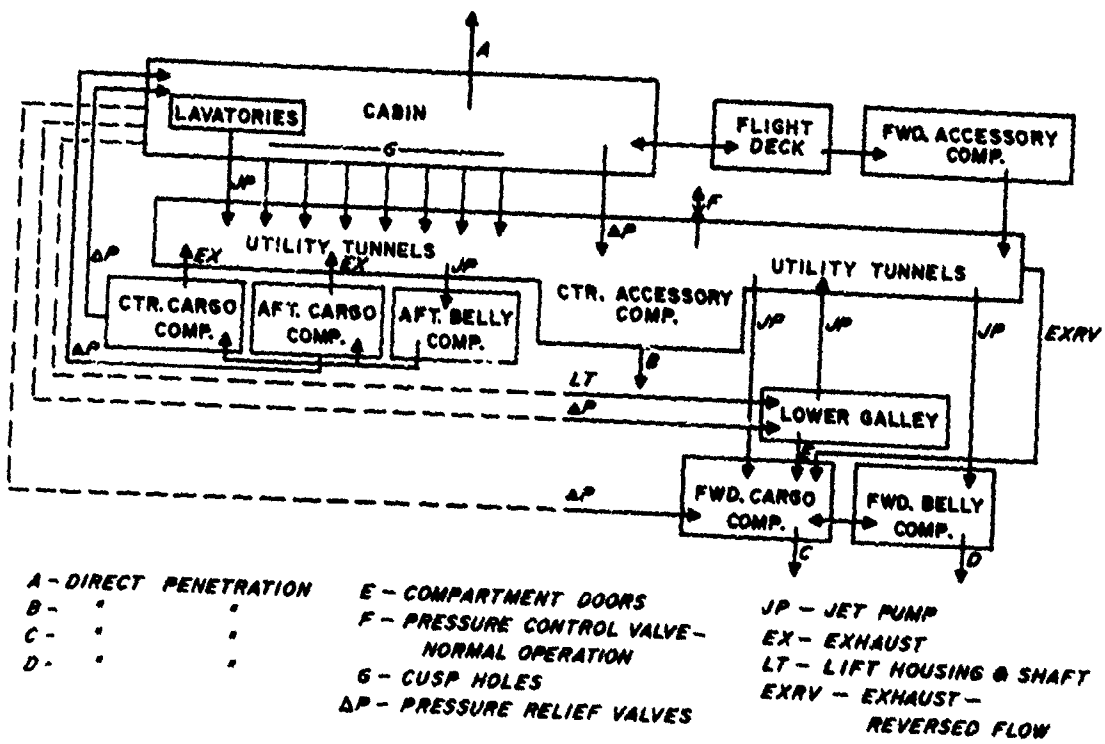

FIGURE 1. Simplified schematic and projected airflow diagram based on decompression events.

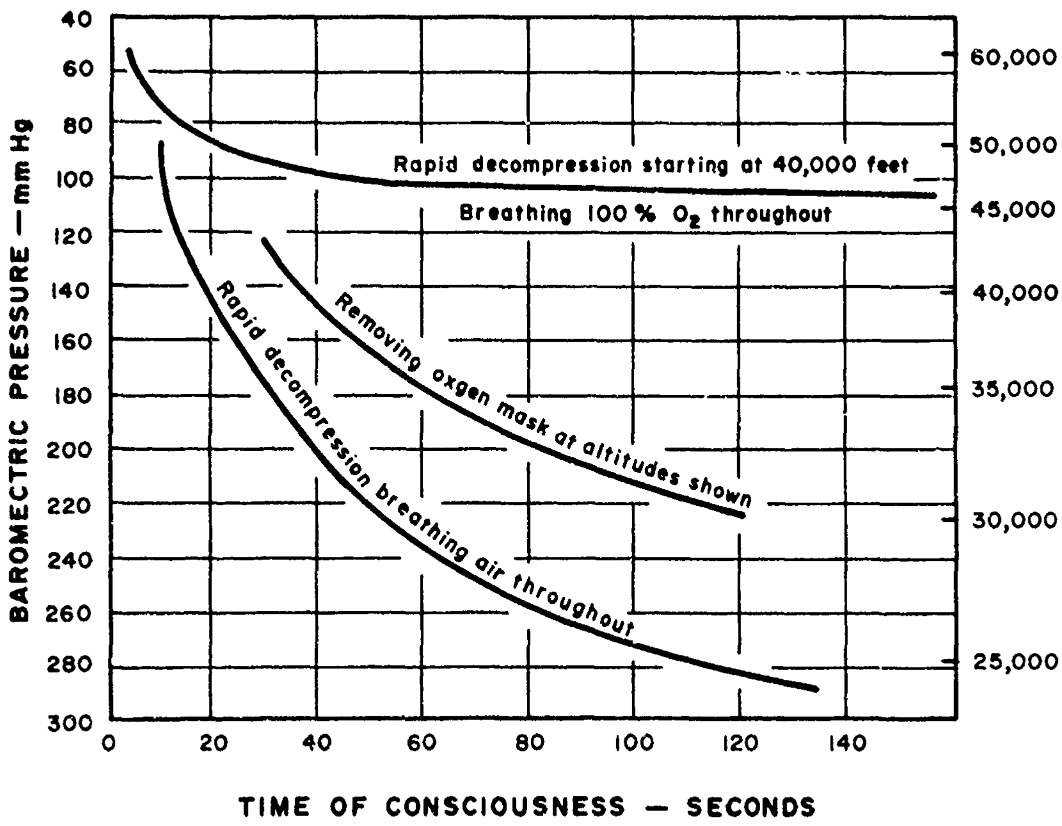

FIGURE 2. Two decompression conditions and the time of consciousness for each type as a function of barometric pressure at the end of decompression and for comparison of a third curve showing the effect of removing the oxygen mask at altitudes from 30,000 to 43,000 ft. The rapid decompressions shown for air breathing throughout start at 10,000 ft. (Adapted from AF Manual 160-5, 1954; and Blockley and Hanifan, final report on contract FA-955, FAA, 1961.)

Their equation for defining a rapid decompression is:

$$t_E = \left(\frac{Vc}{A \cdot S}\right)\left(P_1\right)$$

Where: t_E = total time of decompression in seconds

Vc = volume of the compartment in cubic feet

A = area of leak orifice in square feet

S = speed of sound in feet per second

P_1 = nonlinear function of $\frac{Pc-Pa}{Pc}$

Pc = compartment pressure

Pa = absolute pressure

The aircraft decompression resulted from four basic penetrations in the fuselage: (i) the loss of one cabin window; (ii) penetrations into the center accessory compartment; and (iii) two penetrations into the forward cargo and belly compartments.

Openings into the forward cargo and belly compartments consisted of a forward penetration with an area of 230 in^2 and an aft penetration with an area of 140 in^2. The forward penetration was clean, passing through the fuselage and inner liner. The aft penetration was complete through the fuselage; however, the inner liner was in place, though ruptured. This would indicate that the forward penetration occurred first, decreasing the pressure differential followed by the aft penetration.

Two possible decompressions of the forward cargo and belly compartments are presented:

Condition A:

Volume forward cargo compartment		1,375 ft^3
Volume belly compartment		690 ft^3
Total volume		2,065 ft^3
Area forward penetration	230 in^2	
Area aft penetration x ½	70 in^2	
Total area	300 in^2	
Total area approximately	2.1 ft^2	
Pc	590 mmHg	
Pa	148 mmHg	
P_1	2.5	

$$t_E = \left(\frac{2{,}065\ ft^3}{(2.1\ ft^2)\ (1{,}130\ ft/s)}\right)\left(P_1\right)$$

t_E = approximately 2.2 s

Condition B:

Total volume	2,065 ft^3
Area forward penetration (aft penetration not included)	230 in^2
Total area approximately	1.60 ft^2

$$t_E = \left(\frac{2{,}065\ ft^3}{(1.60\ ft^2)\ (1{,}130\ ft/s)}\right)\left(P_1\right)$$

t_E = approximately 2.8 s

While these decompression times are only estimates, they do reflect the severity of the decompression in the forward cargo and belly compartments, the result of a large penetration area working against a small volume.

The forward cargo compartment is separated from the lower galley by two cargo doors. These doors, though closed, do not constitute a pressure-tight bulkhead. There is a rubber seal mounted around the perimeter of each door on the forward face. With a decompression in the forward cargo compartment, the pressure differential would force the doors away from this seal. The lack of detectable damage to these doors indicates a rapid decompression in the lower galley, controlling the pressure differential between the two compartments.

Using the equation of Haber and Clamann (7), a decompression for the galley compartment could be estimated as follows:

Condition A:

Volume of lower galley	1,670 ft^3
Area of orifice 1/8 in x 220 in x two doors	55 in^2
Area of orifice (approximately)	0.38 ft^2

$$t_E = \left(\frac{1{,}670\ ft^3}{(0.38\ ft^2)\ (1{,}130\ ft/s)}\right)\left(P_1\right)$$

t_E = approximately 9.7 s

Condition B: The effective opening of 1/8 in restricted to one-half the perimeter of the doors.

Volume of lower galley	1,670 ft^3
Area of orifice 1/8 in x (½ x 220) in x two doors	28 in^2
Area of orifice approximately	0.19 ft^2

$$t_E = \left(\frac{1{,}670\ ft^3}{(0.19\ ft^2)\ (1{,}130\ ft/s)}\right)\left(P_1\right)$$

t_E = approximately 18.5 s

Condition C: Condition B with a decompression to 30,000 ft equivalent.

Volume of lower galley	1,670 ft^3
Area of orifice approximately	0.19 ft^2
Pa equivalent to 30,000 ft	225 mmHg
P_1	1.5

$$t_E = \left(\frac{1{,}670\ ft^3}{0.19\ ft^2)\ (1{,}130\ ft/s}\right)\left(P_1\right)$$

t_E = approximately 11.1 s

The decompression in the lower galley was basically due to the loss of pressure in the forward cargo compartment and, as such, should be treated as a dependent function. The number of unknowns, such as input flow to the lower galley from the air conditioning system, the lift compartment, and the pressure relief valve and additional outflow through the galley exhaust jet pump (as presented in the decompression schematic) make a detailed mathematical analysis impractical. These estimates support the conclusion of a rapid decompression to an equivalent altitude of around 30,000 ft. A decompression of this magnitude would be in agreement with the observations and physiological reactions of the flight attendants.

A significantly different decompression profile occurred in the passenger cabin. In the upper deck, two penetrations of 160 in^2 each occurred. One penetration, directly in the passenger cabin, was the loss of the window at seat 17H. The other penetration was in the center accessory compartment. The large area of cusp holes that join the passenger cabin to the utility tunnels and hence to the accessory compartment effectively places this penetration in the passenger cabin (Figure 3). While these penetrations are large, they are working against a large cabin volume, 16,600 ft^3, and a high input from the No. 1 and No. 2 compressors, 150 lb air/min each.

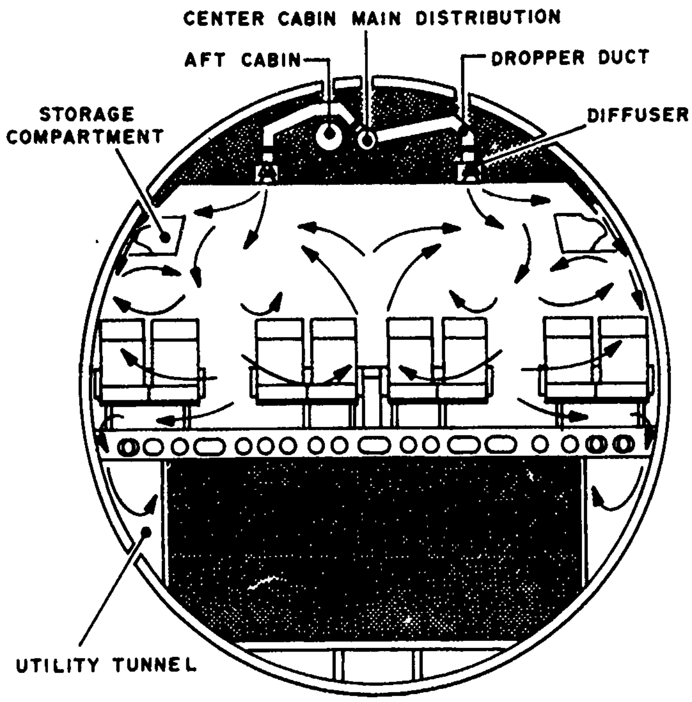

FIGURE 3. Cabin air circulation and exhaust diagram.

The high background noise described by the pilot might be associated with the rapid movement of air through openings in the deck of the flight compartment to the forward accessory compartment, hence to the utility tunnels and out the penetration in the center accessory compartment. This background noise could also be associated with the rapid expansion of input air from the inlet ports, the result of an increased pressure differential. A rate change in altitude of 5,000 ft/min was observed on the cabin altitude rate indicator; however, maximum cabin altitude was not determined.

The "No Smoking" passenger warning signs and cabin overhead lights were observed to be on, indicating the passenger cabin had passed through the 10,000-ft equivalent altitude.

Statements by the flight attendants describe a mild to moderate decompression in the passenger cabin. The absence of fainting by passengers and attendants who, in some cases, performed considerable activity without supplemental oxygen, indicates the maximum equivalent altitude reached in the passenger cabin to be less than 18,000-20,000 ft.

In effect, two different decompressions are identified: a rapid and severe decompression in the lower compartments, and a slower and less severe decompression in the upper compartments.

VI. Summary.

1. Lower deck galleys should be prohibited in future production aircraft.

2. All oxygen systems intended for use in lower galleys should have a dual presentation system, one slaved to the upper deck aneroid switch and one coupled to an aneroid switch in the lower galley. This oxygen unit should also be manually accessible.

3. A close examination should be made of the electrical systems and operational procedures to insure that electrical power for mask presentation is maintained.

4. The seat back oxygen system should be reengineered to: (i) make removal of the canisters by passengers improbable; (ii) improve the thermal isolation of the canister; (iii) change the mask bracket to preclude lanyard entanglement; and (iv) modify the mask to prevent separation of the reservoir bag from the facepiece.

5. Improve flight attendant training in the use and theory of oxygen generation systems and in manual access techniques to emergency equipment.

6. Design the oxygen containers in the attendant seat installations to preclude entry of dirt and trash into the interior of the unit.

7. Attendant portable oxygen units should be accessible and immediately usable. The use of plastic bags around these units should be discontinued.

8. The K-S disposable face mask does not provide sufficient protection in the event of severe decompressions. These masks should be immediately removed from all air carrier aircraft and replaced with masks approved to FAA TSO-C64.

9. Examine the effect on potential injuries of deployed seat back oxygen systems during emergency landings where impact would be encountered.

10. Conduct a detailed study of the pressure differentials that develop in and through the lift shaft as a result of rapid decompressions in the lower galley.

11. Examine the pressure differentials that develop through and across compartments as a result of rapid decompression.

12. Include cabin pressure as a component of the flight recorder.

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EFFECTIVENESS OF A PAPER CUP AS AN AID TO PROVIDING OXYGEN TO LARYNGECTOMEE PASSENGERS

E. B. McFadden

Several air carriers have incorporated instructions in their training manuals describing the disconnection of the standard phase-dilution passenger oxygen mask and insertion of the oxygen hose through a hole punched in the bottom of a paper cup for administering first aid oxygen to laryngectomee passengers. The use of a paper cup attached to a hose delivering a continuous flow of oxygen to a tracheostomy breather, or even to an oral breather, is a most inefficient and ineffective approach to administering first aid or emergency oxygen.

The characteristics of human respiration as related to the administration of oxygen by continuous flow are not generally well understood. The inadequacy of the paper cup technique may be illustrated by considering the following characteristics and approximate values of respiration for an individual at rest: (1,2)

<u>Minute Volume</u> - 7 L/min (total volume of air breathed over a span of 1 minute in liters per minute)

<u>Tidal Volume</u> - 0.7 L (volume of air breathed each breath in liters)

<u>Respiration Rate</u> - 10 (number of respiratory excursions over a span of 1 minute)

Where: $\text{Respiratory Rate} = \dfrac{\text{Minute Volume}}{\text{Tidal Volume}} = \dfrac{7\ \text{L/min}}{0.7\ \text{L}} = 10$

and

$\text{Tidal Volume} = \dfrac{\text{Minute Volume}}{\text{Respiratory Rate}} = \dfrac{7\ \text{L/min}}{10} = 0.7\ \text{L}$

or

$\text{Minute Volume} = \text{Respiratory Rate} \times \text{Tidal Volume} = 10 \times 0.7\ \text{L} = 7.0\ \text{L/min}$

The peak inspiratory flow is the rate at which air is inspired during the 1.0 to 1.5 seconds of each tidal volume (at a <u>rate of three to four times the minute volume</u>) (1,2), which would in this case approximate 25 to 30 L/min. Moderate exercise or activity may increase <u>the peak inspiratory</u> flow to 60-65 L/min.

If one considers that the maximum oxygen flow required from a first aid portable oxygen cylinder is 4 L/min STPD* per

*STPD - Standard temperature $0^{o}C$, pressure 760 mmHg, dry.

FAR 25.1443 (there may be a means to reduce flow to 2 L/min), then the maximum oxygen available by the paper cup technique may be estimated.

An 8-oz cup is considered to be a nondistensible container with a total maximum volume of 0.24 L. At the instant inspiration is initiated, assume the cup contains 0.24 L of 100 percent oxygen and during the 1.5 s of inspiration an additional 0.099 L of oxygen is introduced into the cup (at a flow rate of $\frac{4 \text{ L/min}}{60} = 0.066$ L/s, 0.066 L/s x 1.5 s = 0.099 L). The cup will not contain 100 percent oxygen because it contains large quantities of air and some carbon dioxide from the previous exhalation.

(a) The maximum oxygen available during a 1.5-s inspiration is:

Volume of 8-oz cup	0.240 L
Volume of oxygen added during inspiration	0.099 L
	0.339 L
	or 0.34 L

(b) The theoretical percentage of oxygen that could be added to air $= \frac{0.34}{0.7} = 49\%$.

This calculation assumes no leakage of air around the periphery of the cup or leakage through the opening in the cup through which the hose is inserted. However, in practice, extensive leakage is required because the cup, being noncompliant, must instantly on initiation of inspiration allow ambient air to be drawn into the system to replace oxygen removed from the cup in order to satisfy the remainder of the 0.7-L tidal volume requirement.

The calculation above also theorizes that during exhalation the cup is refilled by a continuous flow of oxygen. Even though oxygen is flowing into the cup during exhalation, the act of exhalation continuously washes out the small amount of oxygen (0.3 L) introduced during the 4.5 s prior to the next inspiration and leaves the cup with a high concentration of carbon dioxide and air exhaled from the previous inspiration. This residual constitutes the initial gas inhaled on the next inspiration rather than the theoretical 100 percent oxygen referred to above. Therefore, the calculation is not representative of the true situation.

If one considers the paper cup to be rigid extension of the oxygen hose supplying oxygen at a continuous flow rate of 4 L/min, and during each inspiratory event air is being inspired at a rate of 25 L/min, then during inspiration oxygen is mixed and added to air according to the following percentage.

(c) $\frac{\text{Oxygen flow}}{\text{Peak inspiratory flow}} = \frac{4 \text{ L/min}}{25 \text{ L/min}} = 16\%$

It would appear that standard phase-dilution passenger masks qualifying to FAA TSO-C64 and National Aerospace Standard 1179 would be a better alternative. These masks in the form of a cylinder or modified cone conform to various contours with the mask facepiece terminating in a circular opening (2½-3½ in) approximating that of the paper cup (3 in). The phase-dilution mask incorporates a 1.10-L reservoir bag that stores 100 percent oxygen during exhalation and allows the wearer to breath 100 percent oxygen at the beginning and throughout inspiration if the reservoir bag is full and the tidal volume does not exceed 1.10 L including the flow added during inspiration.

The phase-dilution mask provides a large quantity of 100 percent oxygen at the initiation of inspiration, which is delivered to the physiologically active areas of the lungs. It the tidal volume exceeds 1.10 L (plus the quantity of oxygen added by continuous flow during inspiration), a check valve opens to admit ambient air. Ambient air may only penetrate into the trachea, bronchi, and bronchials, which are nonphysiologically active areas of the respiratory system. Under these conditions the ambient air introduced does not dilute the high concentration of oxygen in the alveoli of the lungs yet is used to fulfill a portion of the respiratory demand. On exhalation the ambient air is swept from the mask and replaced by alveolar gas high in oxygen concentration, which constitutes the initial portion of the subsequent inhalation. If one applies the criteria of (c) and assumes no leakage or tidal volumes in excess of the volume of the reservoir bag, then the calculation in (c) for a phase-dilution mask is as follows:

(d) $\frac{\text{Oxygen flow}}{\text{Minute volume}} = \frac{4\ \text{L/min}}{7\ \text{L/min}} = 57\%$

FAR Part 25.1443 specifies 4 L/min STPD. At a cabin altitude of 5,000 ft, 4 L/min STPD is increased to 5.9 L/min BTPS*, increasing all of the above percentages.

However, the assumption of a 7 L/min minute volume is conservative. The data of Ernsting (2) indicates that seated, inactive flight crewmembers exhibit a minute volume of 10-15 L/min BTPS, nearly twice the above value. Applying the more realistic value of Ernsting (2) (a minute volume of 15 L/min, peak inspiratory flow of 55 L/min and at a cabin altitude of 5,000 ft), estimation of oxygen added to the inspired air by the paper cup and by the mask may be calculated as follows:

(e) Oxygen added to inspired air by paper cup $= \frac{5.9\ \text{L/min}}{55\ \text{L/min}} = 10.7\%$

*Body temperature 98.6°F, pressure 532 mmHg, saturated with water vapor.

(f) Oxygen added to air by mask $= \frac{5.9 \text{ L/min}}{15 \text{ L/min}} = 39.3\%$

In the case of the phase-dilution mask, it is assumed that the respiratory rate increases from 10 to 12 in response to the increase in minute volume. Tidal volume is then increased:

$$\text{Tidal Volume} = \frac{15 \text{ L/min}}{12} = 1.25 \text{ L}$$

The capacity of the reservoir bag under these conditions is equal to:

Capacity of the reservoir bag + oxygen added during 1.5 s inspiration = 1.10 L + .15 L = 1.25 L

The reservoir bag, therefore, exhibits a capacity equal to the tidal volume. If oxygen were being delivered at a rate of 15 L/min there would be no dilution. However, oxygen delivered to the reservoir is only 5.9 L/min or $\frac{5.9 \text{ L/min}}{12} = 0.49$ L/min per breath and dilution according to equation (f) occurs.

The calculations and values presented in this discussion are approximations and simplifications of more complex respiratory equations and do not take into consideration leakage, physiological dead space, and variations in individual discrete tidal volumes. However, these calculations illustrate the superior efficiency and performance of an oxygen-dispensing device for use with continuous-flow oxygen that incorporates a means for the collection and storage of oxygen prior to each individual inspiration.

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PHYSIOLOGICAL CONSIDERATIONS AND LIMITATIONS IN THE HIGH-ALTITUDE OPERATION OF SMALL-VOLUME PRESSURIZED AIRCRAFT

E. B. McFadden and D. deSteiguer

I. Introduction.

Several small-volume, pressurized, general aviation jet aircraft are currently certified to operate at a maximum altitude of 13,716 m (45,000 ft), and flight to 15,240 m (50,000 ft) is under consideration. While these aircraft may be qualified, from an engineering analysis, for operation at these altitudes, a question remains as to the physiological consequences to the crew and passengers of an aircraft in the event of a decompression of the pressurized cabin. A review of aircraft operational history demonstrates that such decompressions do occur in both air carrier and pressurized general aviation aircraft designed with the best of modern technology (1,2). This paper reviews the capabilities and limitations of oxygen equipment and the operational procedures for preventing hypoxia and thus its incapacitating effects in the event of decompression to altitudes within the operational regime of these aircraft. The various other physiological and psychological effects of rapid decompression, which may contribute to and/or produce incapacitation with or without the existence of hypoxia, are not discussed in this paper even though they may compound the difficulty of survival.

II. Discussion.

Aircraft Decompression Factors. The rate and severity of aircraft decompressions have been defined and discussed by Fritz Haber and Hans Clamann (3) of the USAF School of Aviation Medicine.* These authors define two factors in a decompression, a time constant (t_c) and a nonlinear function of pressure (P), with the time of decompression (T_D) being the product of these factors ($T_D = t_c P$). The time constant is defined as the volume of the cabin divided by the product of the area of the leak orifice and the speed of sound in air. The pressure factor is a nonlinear function of the difference between cabin and ambient air pressures divided by the cabin pressure. For a cabin equivalent altitude of 2,438 m (8,000 ft) and a flight altitude of 15,240 m (50,000 ft), this factor has a value of about 3.3.

Typical aircraft volumes and individual window areas are presented in Table 1. From these data, and with a knowledge of cabin and flight altitudes, one may estimate the size of the leak orifice or defect area for a given cabin volume to decompress to an altitude of 15,240 m (50,000 ft) in a given time interval. Data on 10-s decompressions from 2,438 to 15,240 m (8,000 to 50,000 ft) for cabin volumes of 7.5 m^2 and 17.8 m^2 (265 ft^2 and 630 ft^2) are presented in Table 2. It will be noted that the

*Now the USAF School of Aerospace Medicine.

TABLE I

AIRCRAFT TYPES, TYPICAL APPROXIMATE VOLUMES, AND CABIN WINDOW AREAS

Aircraft Model	Pressurized Volume		Cabin Window Area	
	m^3	ft^3	cm^2	in^2
LR-24, 25	7.5	265	2684	416 (a)
NA-265	12.2	430	839	130
NAR-1121	12.5	440	903	140
DH-125-400	16	565	652	101
DH-125-600	17.8	630	652	101
L-329	35	1,250	1407	218
G-1159	52.4	1,850	2510	389
DC-9	165	5,840	884	137
B-737	227	8,010	903	140
B-727	256	9,045	903	140
DC-8-50	366	12,920	1768	274
B-707	411	14,495	903	140
DC-10	935	33,000	1019	158
L-1011	991	35,000	774	120
B-747	1671	59,000	903	140

(a) Later model 24 and all 25 aircraft are 665 cm^2 (103 in^2)

TABLE II

ESTIMATED 10-SECOND DECOMPRESSIONS TO 15,240 m (50,000 ft) FOR TWO CABIN VOLUMES

	AIRCRAFT A	AIRCRAFT B
Cabin Volume	7.5 m^3 (265 ft^3)	17.8 m^3 (630 ft^3)
Cabin Altitude	2,438 m (8,000 ft)	2,438 m (8,000 ft)
Flight Altitude	15,240 m (50,000 ft)	15,240 m (50,000 ft)
Time of Decompression	10 s	10 s
Approximate Area of Orifice	697 cm^2 (10.8 in^2)	167 cm^2 (25.9 in^2)
Approximate Diameter of Orifice	9.4 cm (3.7 in)	14.5 cm (5.7 in)

area required to produce these decompressions is only about one-fourth the area of the cabin window. Simple calculations such as these can only be approximations because of variables of orifice configuration and location, flow efficiency, thermodynamic considerations, and compressor input rates as well as numerous other factors. Because civilian aircraft flight recorders do not record cabin pressure, the correlation of decompression calculations with actual in-flight incidents is difficult, if not impossible.

For example, reconstruction of the cabin altitude profile of the DC-10 decompression near Albuquerque, New Mexico (4), required approximately 7 mo and relied extensively on analysis of the cockpit voice-recorder tapes. By relating segments of time from the initial sound of decompression and the automatic initiation and cessation of pressure breathing as provided by the flight deck crew mask-mounted regulators, reconstruction of the cabin altitude profile was possible.

Aerodynamic Effects. Negative differentials following decompression may occur and the cabin altitude may actually exceed the flight altitude as a result of the aerodynamic (Venturi) effect. Blockley and Hanifan (5) describe this phenomenon in large (bomber) aircraft. The removal of doors and hatches at 12,192 m (40,000 ft) and Mach 0.87 produced an increase in cabin altitude of 610 to 2,438 m (2,000 to 8,000 ft); i.e., 12,802 to 14,630 m (42,000 to 48,000 ft). This effect could be more pronounced at 15,240 m (50,000 ft), because less differential is required to produce an equivalent increase in altitude.

Physiological Considerations. Oxygen equipment should have the capability of providing adequate protection for both crew and passengers in the event of a decompression to the maximum certified altitude of the aircraft. Alveolar oxygen partial pressure of flight deck crewmembers must be sufficient to prevent hypoxia-induced performance degradation and loss of useful consciousness.

The total pressure within the lungs follows the cabin pressure during a decompression (if it does not, an excess differential may be produced with possible lung damage), instantly altering the partial pressures of oxygen, carbon dioxide, and nitrogen.

The alveolar gas composition for selected altitudes while breathing air is presented in Table 3. An examination of these data shows that in rapid decompressions to altitudes higher than 10,058 m (33,000 ft) while breathing air, the liberation of oxygen from the blood into the lungs (i.e., reverse diffusion) begins. This condition is demonstrated (Table 3) by the percentage of oxygen increasing above that of air (20.9%). However, the partial

TABLE III

ALVEOLAR GAS COMPOSITION 2-5 SECONDS FOLLOWING RAPID DECOMPRESSIONS TO SELECTED ALTITUDES WHILE BREATHING AIR (COMPILED FROM CLAMANN, ET AL.[11])

	ALTITUDE			
	10,058 m 33,000 ft	12,192 m 40,000 ft	13,990 m 45,900 ft	15,240 m 50,000 ft
Pressure, total mmHg	197	141	105	87
Partial pressure, H_2O	47	47	47	47
Pressure, dry gas	150	94	58	40
	DRY GAS COMPOSITION			
Partial pressure, O_2	30	22	14	11
Percentage	19.8	23.4	24.7	27.0
Partial pressure, CO_2	33	27	24	16
Percentage	22.0	29.1	41.6	40.3
Partial pressure, N_2	87	45	20	13
Percentage	58.0	47.5	34.4	32.7

pressure of oxygen is simultaneously reduced in response to a reduction in total ambient pressure and to the increased diffusion of carbon dioxide into the alveoli from the venous blood. Loss of consciousness generally follows when the alveolar pO_2 drops below 20 mmHg, while a decrease in performance generally occurs at alveolar pO_2 values below 35 mmHg.

The alvolar gas composition for selected altitudes while breathing oxygen is presented in Table 4. An examination of these data demonstrates the dangerous alveolar pO_2 level following rapid decomressions to 15,240 m (50,000 ft) even though oxygen was prebreathed.

Breathing Air Prior to Decompression. Crew and passengers breathing air at a cabin altitude of 2,438 m (8,000 ft) prior to rapid decompression to 15,240 m (50,000 ft) would lose useful consciousness even though they had donned oxygen masks at the beginning of decompression. In addition to washout of nitrogen from the respiratory system, the air in the mask and the regulator hose must also be replaced with oxygen. Mask-mounted regulators and equipment modifications tend to alleviate the problem of equipment dead space, but little can be done to modify the human lung nitrogen washout short of wearing a mask and breathing oxygen prior to the decompression. Data obtained in this laboratory on quick-donning crew oxygen masks during decompressions, simulating a B-707 decompression, illustrated the delay imposed by nitrogen washout (6) (Figure 1). Hyperventilation may accelerate nitrogen washout to some degree but is in itself a dangerous expedient.

An analysis by Blockley and Hanifan (5) indicates that following a 1.5-s decompression from 2,438 to 15,240 m (8,000 to 50,000 ft) (for subjects breathing air prior to the decompression), the alveolar pO_2 is predicted to drop below 20 mmHg and produce loss of consciousness with no possibility of recovery at this cabin altitude, even though 100 percent oxygen is breathed 3 s after the start of decompression.

Rapid decompression experiments conducted by Baron (7) in which two subjects breathing air were decompressed in 5 s--one from 2,438 to 13,661 m (8,000 to 44,820 ft) and one from 2,438 to 13,714 m (8,000 to 44,995 ft)--confirm these predictions. Even though both subjects donned or attempted to don their masks 12 s from the start of decompression and the dwell time at maximum altitude was limited to 5 to 6 s, both subjects lost useful consciousness 14 to 16 s after the start of decompression. Other subjects in this series were unable to complete a simple performance test even though they had donned their masks in 8, 5, or even 3 s after the start of decompression.

TABLE IV

ALVEOLAR GAS COMPOSITION 2-5 SECONDS FOLLOWING RAPID DECOMPRESSIONS TO SELECTED ALTITUDES WHILE BREATHING OXYGEN (COMPILED FROM CLAMANN *ET AL.*[11])

	ALTITUDE			
	10,028 m 32,900 ft	12,009 m 39,400 ft	13,503 m 44,300 ft	15,240 m 50,000 ft
Pressure, total mmHg	198	145	115	87
Partial pressure, H_2O	47	47	47	47
Pressure, dry gas	151	98	68	40
	DRY GAS COMPOSITION			
Partial pressure, O_2	107	71	45	20
Percentage	70.6	72.0	66.4	50.6
Partial pressure, CO_2	35	23	19	18
Percentage	23.4	23.6	28.0	44.2
Partial pressure, N_2	9	4	4	2
Percentage	6.0	4.4	4.6	5.2

All decompressions from 1,006 m (3,300 ft).

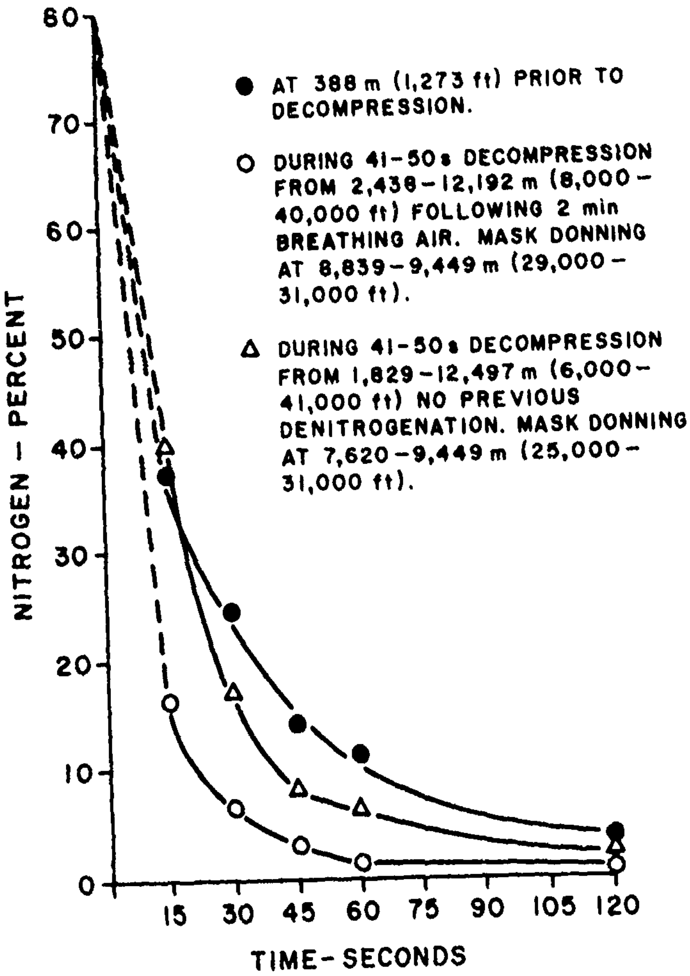

FIGURE 1. Nitrogen washout prior to and during decompression. Quick-donning crew oxygen mask and panel-mounted pressure demand regulator.

Noble et al. (8) report a case history of a pilot who, on experiencing a decompression of a T-39 (Sabreliner) aircraft at 13,716 m (45,000 ft), lost consciousness within an estimated time comparable to those above.

Breathing Oxygen Prior to Decompression. Luft (9) describes experiments in which subjects wearing masks and breathing 100 percent oxygen at 10,058 m (33,000 ft) were rapidly decompressed to altitudes of 15,850 to 16,154 m (52,000 to 53,000 ft). If the total exposure to the latter altitudes exceeded 6 s, subjects lost consciousness about 16 s from the beginning of decompression even though they breathed 100 percent oxygen throughout the experiment.

Additional data detailing the limits of protection afforded by prebreathing oxygen have been presented by Blockley and Hanifan (5) (in a review of German Air Force data) and Luft et al. (10). These data show that even though 100 percent oxygen was breathed before and during rapid decompressions to 15,240 m (50,000 ft), loss of consciousness occurred in 20 to 23 s.

Breathing Oxygen Under Pressure. Limited relief to this dilemma can be achieved through pressure breathing. Blockley and Hanifan (5) state that wearing a mask prior to rapid decompression to a maximum altitude of 15,240 m (50,000 ft) may prevent loss of consciousness provided the regulator is designed to deliver at least 90 percent oxygen at normal cabin pressure. However, the regulator must instantly provide positive pressure breathing with the mask tightly sealed against the face in order to intercept and reverse the rapid decline in alveolar oxygen partial pressure. Rapid increase in the diffusion of venous carbon dioxide into the lungs compounds this problem by jeopardizing the recovery of an adequate alveolar oxygen partial pressure.

For positive pressure breathing to be effective, the individual must be recently highly trained; otherwise, he may involuntarily hyperventilate to a point of hypocapnia-induced incapacitation. Calculated alveolar oxygen histories at 15,240 m (50,000 ft) for the three previously described situations are shown in Figure 2.

For certain research operations by highly trained crewmembers, marginal protection may be provided by a flight deck procedure wherein the pilot and copilot alternate in wearing a pressure-demand mask connected to an appropriate pressure-breathing regulator supplying no less than 90 percent oxygen. Upon decompression, the regulator must automatically initiate pressure breathing to a level consistent with altitude requirements. For this procedure to be fully effective, the crewmember breathing oxygen should remain on oxygen until the relieving crewmember accomplishes adequate nitrogen washout; otherwise, both crewmembers would be vulnerable should decompression occur during the exchange of this function.

Pressure Breathing With Counterpressure. Using a partial-pressure vest (a pressure jerkin or partial-pressure suit) in combination with prebreathing 100 percent oxygen and pressure breathing is a safer alternative.

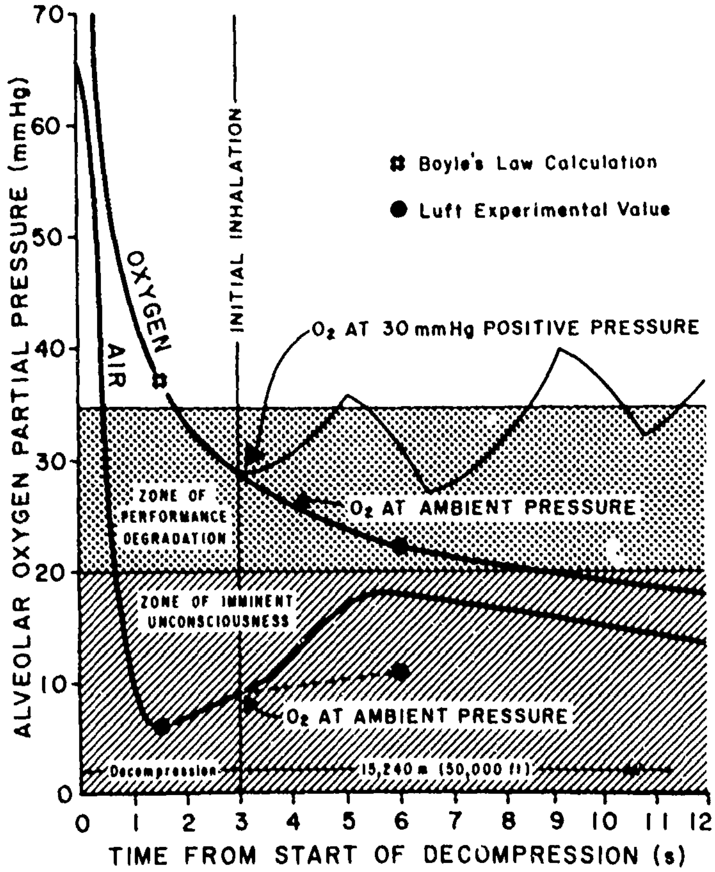

FIGURE 2. Calculated alveolar oxygen histories at 15,240 m (50,000 ft) (After Blockley).

III. Summary.

In the event of rapid decompression to flight altitudes of 15,240 m (50,000 ft), the following considerations are paramount:

A. If masks are not in use and air is being breathed, loss of consciousness will occur in approximately 16 s or less. The use of quick-don masks will be ineffective in preventing loss of consciousness.

B. Even if masks are worn and 100 percent oxygen is prebreathed, loss of consciousness will still occur in approximately 20 s.

C. If pressure breathing is used and at least 90 percent oxygen is not prebreathed, residual nitrogen in the alveoli may negate the advantages of pressure breathing.

D. If pressure breathing is used and 90 to 100 percent oxygen is prebreathed, a highly trained, physically fit individual may tolerate the pressures required to maintain useful consciousness. Using a counterpressure garment and pressure breathing combined with prebreathing 90 to 100 percent oxygen is a safer alternative.

E. In decompressions of the severity under consideration, it may be assumed that passengers will lose consciousness. The ultimate physiological consequences and recovery will be dependent not only on the decompression but also on other factors, such as duration of exposure, age, weight, and past medical history. If sufficient protection is to be provided the passenger, he or she must be able to tolerate pressure breathing, be highly trained, and be wearing pressure-breathing oxygen equipment prior to decompression.

F. The marginal safety of rapid decompressions to 13,716 m (45,000 ft) is rapidly degraded with further increase in altitude and at 15,240 m (50,000 ft), even the breathing of 100 percent oxygen before and after decompression will fail to prevent loss of consciousness. The extended exposure time at critical altitudes as a result of increased descent time, the possibility of the Venturi effect, and additional physiological insults of decompression to 15,240 m (50,000 ft) compound the hazard.

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OXYGEN CONCENTRATIONS IN THE VICINITY OF A PASSENGER RECEIVING FIRST AID OXYGEN

E. B. McFadden and M. S. Pinski

I. Introduction.

To preclude providing an ignition source, smoking aboard air carrier aircraft is prohibited at arbitrary distances or at specified seat rows from passengers who are receiving first aid oxygen. The basis for these separational distance requirements and whether they are adequate or unduly restrictive are not known.

During the administration of first aid oxygen less than 10 percent of the oxygen breathed is normally adequate to meet metabolic needs; the remaining 90 percent is discharged into the ambient air. With increased oxygen flow, 96 to 98 percent of the oxygen may be discharged into the surrounding area. Knowledge of the extent to which the surrounding air is increased in oxygen content would allow a more realistic evaluation of the modification of the flammability of materials in the immediate vicinity of the oxygen source.

Utilizing modern state-of-the-art analytical instrumentation, we conducted a brief preliminary study of the oxygen content of the air surrounding a subject breathing 100 percent oxygen to chart localized oxygen concentrations vs. distance from the subject. This study does not concern the social acceptability or health hazard potential of smoking.

II. Methods.

The subject was seated in a room where there was probably some degree of airflow, but at a level undetectable by human senses. He then donned a standard passenger oxygen mask, designed to FAA TSO-C64 and NAS 1179, and an oxygen flow of 4 L/min was initiated in accordance with that commonly provided by the regulator of a first aid portable oxygen cylinder. The probe of a highly sensitive and accurate mass spectrometer capable of rapid response was utilized to continuously scan oxygen concentrations at various angles and decreasing distances from the subject.

III. Results.

At 6, 5, 4, 3, and 2 ft no increases in oxygen concentration were detected above that for air. As distances were decreased to 1 ft and less, the following increases in oxygen concentration above that of air were detected (Figure 1).

The oxygen flow was then increased to 30 L/min or 7½ times the normal first aid flow with the following results taken at the same points (Figure 2).

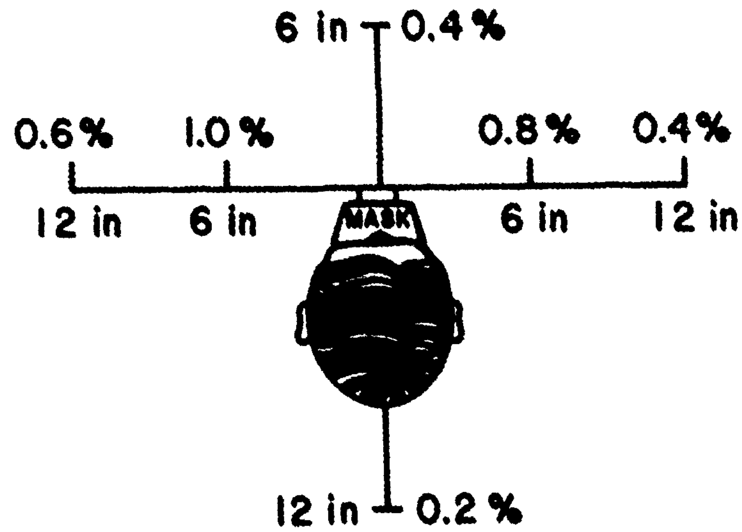

FIGURE 1. Increases in oxygen concentration above that of air at mask level when breathing continuous-flow oxygen at a flow of 4 L/min.

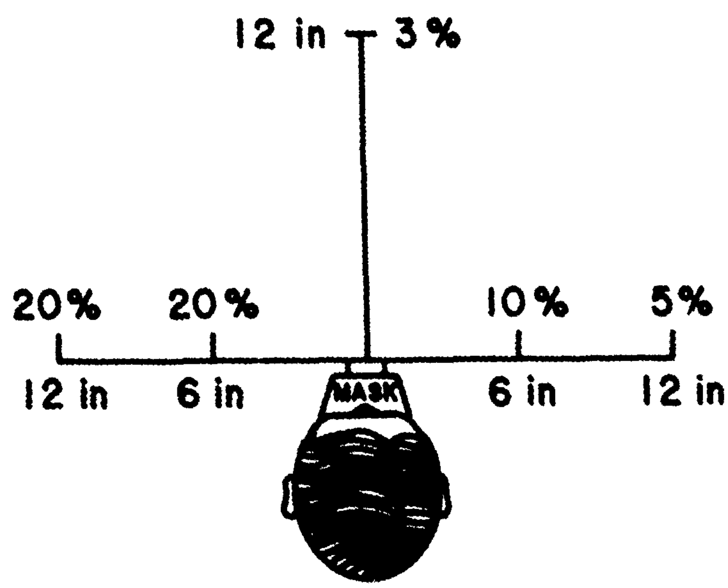

FIGURE 2. Increases in oxygen concentration above that of air at mask level when breathing continuous-flow oxygen at a flow of 4 L/min.

Scans of oxygen concentration were made at approximately 45° above and below mask level but their values did not exceed those at mask level. The design of the exhalation valve of the particular TSO-C64 passenger mask used in this experiment tended to direct the exhaled oxygen toward the sides of the mask and apparently accounted for the higher values detected in this area about the mask.

IV. Discussion.

The U.S. Air Force conducted a study to determine the increase in oxygen concentration in altitude chambers during routine physiological training of flight crewmembers when the chamber was vented and unvented (1). Although it was not stated in the report, these training chambers usually have a volume of approximately 1,000 to 1,500 ft^3 and are occupied by 16 students using demand regulators, each of which would be expected to dump a minimum of 15 to 20 L/min of oxygen into the chamber (240 to 320 L/min total) when on 100 percent oxygen. Even when the chamber was unvented at 25,000 ft, the mean oxygen percentage was only increased from 21 percent (content of oxygen in air) to 27.1 percent for a difference of 6.1 percent. Various studies conducted by the National Aeronautics and Space Administration (NASA) following the Apollo fire have indicated that a concentration of approximately 40 percent oxygen must be approached before there is a significant increase in the flammability of materials. In addition, if 100 percent first aid oxygen is administered in flight to a passenger at a cabin altitude of, for example, 5,000 ft, its partial pressure is reduced from 760 mmHg (14.7 lb/in^2) at sea level to 632 mmHg (12.2 lb/in^2) at 5,000 ft with a tendency to reduce its potential effect on flammability of materials.

Even if an 11-ft^3 first aid oxygen cylinder were to be totally dumped into a DC-9 with a volume of 5,840 ft^3 or a B-747 with a volume of 59,000 ft^3, the resultant increase in oxygen concentration would be infinitely small. In addition, the ventilation capability and rate of air exchange of these aircraft would in all probability make these increases in oxygen concentration unmeasurable.

Considerable caution should be exercised in interpreting the results of this very brief and preliminary evaluation as many factors, such as differences in mask design, quantity and direction of airflow, diverting obstructions, etc., would drastically modify these results.

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